School of Occupational Therapy, Social Work and Speech Pathology

The Postural Control System in Individuals with Autism Spectrum Disorder: Insights from Exploring the Effects of Visual Information on Postural Control

Yi Huey Lim

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Author's Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material that has been accepted for the award of any other degree or diploma in any university.

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee, Approval Number HR 28/2016.

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Statement of Author Contribution

The nature and extent of the intellectual input by the candidate and co-authors have been validated by all authors and can be found in Appendix A.

Yi Huey Lim
(Candidate)

Associate Professor Hoe Lee
(Primary Supervisor)

Dr. Susan Morris
(Co-Supervisor)

Professor Torbjörn Falkmer
(Associate Supervisor)

Professor Garry Allison
(Associate Supervisor)

Professor Tele Tan
(Associate Supervisor)

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Abstract

Background: Postural control is an essential function necessary for humans to perform everyday activities. However, many individuals with autism spectrum disorder (ASD) experience postural control impairments that impact negatively on their mobility at home and in the community. Current knowledge of the postural control system in individuals with ASD is limited due to postural control studies confined mainly to children with ASD and the lack of postural control investigations in dynamic visual environments. Exploring the influence of sensory information on postural control in children and adults with ASD may provide insights into the postural control system in the ASD cohort.

Objectives: This thesis aims to extend the understanding of the postural control system in individuals with ASD. Consequently, the research objectives of thesis were to (1) examine the effect of sensory information on postural control between individuals with ASD and typically developing/developed (TD) individuals and (2) examine the effect of visual information on postural control in children and adults with ASD in relation to TD children and adults.

Methods: Nineteen studies relating to the control of posture in individuals with ASD and TD individuals in a range of sensory conditions were identified through a systematic search of the literature across five databases. Outcome measures assessed using instrumental devices, such as center-of-pressure, were collected. In addition, postural responses of 15 children with ASD, 18 TD children (age range 8 to 12 years old), 15 adults with ASD, and 18 TD adults (age range 18 to 50 years old) were obtained via experimental studies involving assessments of quiet standing in a range of visual conditions. Participants underwent assessments of quiet standing in an immersive and ecologically valid visual environment.

Results: The systematic review found a large effect size when comparing postural control outcomes between individuals with ASD and TD individuals in varying somatosensory and visual conditions. Individuals with ASD tend to show a more unstable posture than TD individuals; this included studies involving both children and adults with ASD. The review also found that individuals with ASD display a predominant mediolateral movement during quiet standing.

In addition, the experimental studies found that, when compared with TD adults, adults with ASD demonstrated a less stable posture when standing still while looking at a central fixation point and while looking at a forward-moving optic flow shown in the peripheral visual field. Adults with ASD also appeared to invest more attention while maintaining their posture when looking at visual stimuli. In contrast, no differences in postural responses between children with ASD and TD children were found. Moreover, there was no difference in the time taken for adults with ASD and TD adults to restore postural stability in response to an initial posture perturbation evoked by changes in the visual environment. Similarly, children with ASD and TD children took the same amount of time to restore their postural stability, but the time was on average 20 seconds longer than that of the adult participants.

Conclusion: There is strong evidence of postural control impairments in individuals with ASD. Postural control impairments are present in both adults and children with ASD. In particular, differences in postural control in response to a range of visual conditions were more obvious between adults with ASD and TD adults as compared with children with ASD and TD children. Furthermore, the postural control system in individuals with ASD appears to be different from TD individuals. The differences may lie in the sensory systems and/or the sensorimotor integration components of those with ASD. Consistent with previous research studies, the results in this thesis suggest the possibility of altered network connectivity within the central nervous systems in ASD. While the present thesis has extended the knowledge of the postural control system in individuals with ASD, the results highlight the need for further investigations to translate experimental findings

into a practical interpretation of the brain, in order to guide the development of postural control interventions for those with ASD.

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Dedication

I dedicate this Ph.D. thesis to God our Heavenly Father and my family.

All glory to Father God for bringing me back to Perth to complete this thesis. Thank you for your provision of favor, courage, strength, and wisdom. This thesis can be completed because God had gone before me and has remained with me throughout this Ph.D. journey. This thesis is truly a product of faith, hope, and love from God. Praise the Lord!

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> ***"The Lord himself goes before you and will be with you; he will never leave you nor forsake you. Do not be afraid, do not be discouraged." Deuteronomy 31:8.***

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List of Abbreviations

º	Degree
AP	Anteroposterior
ASD	Autism spectrum disorder
cm	Centimeters
COP	Center-of-pressure
COPy	Center-of-pressure in the anteroposterior/sagittal plane
CV	Central visual field
EC	Eyes closed
EO	Eyes open
EOS	Eyes open with altered somatosensory
FV	Full visual field
HIVE	Hub for Immersive Visualization and eResearch
HREC	Human Research Ethics Committee
Hz	Hertz
ICF	International Classification of Functioning, Disabilities and Health
IQ	Intelligence quotient
kg	Kilograms
m	Meters
m/s	Meters per second
ML	Mediolateral
mm	Millimeters
mm/s	Millimeters per second
N	Newtons
NT	Neurotypical
PV	Peripheral visual field
RMS	Root mean square
s	Seconds
SE	Sample entropy
SRS	Social Responsiveness Scale
TD	Typically developed/developing
VEL	Velocity
WASI	Wechsler Abbreviated Scale of Intelligence
WHO	World Health Organization

List of Publications

This doctoral thesis consists of the following publications presented in the order of appearance within the thesis:

Lim, Y.H., Partridge, K. Girdler, S., & Morris, S. (2017). Standing postural control in individuals with autism spectrum disorder: Systematic review and meta-analysis. *Journal of Autism and Developmental Disorders, 47*(7), 2238-2253. https://doi.org/10.1007/s10803-017-3144y. Cited 24 times. Journal Impact Factor: 2.768 and SCImago Journal Rank (2018): Q1, 1.68.

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Lim, Y. H., Lee, H. Falkmer, T., Allison, G., Tan, T., Lee, W. L., & Morris, S. (2018). Effect of optic flow on postural control in children and adults with autism spectrum disorder. *Neuroscience, 393*, 138-149. https://doi.org/10.1016/j.neuroscience.2018.09.047. Cited 3 times. Journal Impact Factor: 3.244 and SCImago Journal Rank (2018): Q2, 1.48.

Lim, Y. H., Lee, H. C., Falkmer, T., Allison, G. T., Tan, T., Lee, W. L., & Morris, S. L. (2019). Postural control adaptation to optic flow in children and adults with autism spectrum disorder. *Gait & Posture, 72*, 175-181. https://doi.org/10.1016/j.gaitpost.2019.06.007. Journal Impact Factor: 2.414 and SCImago Journal Rank (2018): Q1, 1.16.

List of Conference Presentations

This doctoral thesis consists of the following conference presentations completed during the duration of the thesis:

Lim, Y. H., Lee, H. Falkmer, T., Allison, G., Tan, T., & Morris, S. L. Vision, balance and autism: How do they all come together? Oral presentation at the annual Australasian Society for Autism Research (ASfAR) Conference. 2016. Perth, WA, Australia.

Lim, Y. H., Lee, H. Falkmer, T., Allison, G., Tan, T., & Morris, S. L. Increased center of pressure regularity during quiet stance in adults with autism spectrum disorder. Poster session at the annual International Meeting for Autism Research (IMFAR) Conference. 2017. San Francisco, California, the United States of America.

Lim, Y. H., Lee, H. Falkmer, T., Allison, G., Tan, T., & Morris, S. L. Larger mediolateral sway in adults with autism spectrum disorder during standing. Oral presentation at the annual Symposium for Western Australian Neurosciences (SWAN). 2017. Perth, WA, Australia.

Lim, Y. H. & Morris, S. L. Optic flow VR: A technique to probe subconscious perception of visual motion. Poster presentation at the annual OzViz. 2017. Perth, WA, Australia.

Chapter 1 Introduction

David loves running. He enjoys the wind in his face as he races around the tracks. However, very often, he trips and falls because he has problems maintaining his posture. David will likely have postural control problems his whole life. They are a feature of his condition – autism spectrum disorder (ASD).

Postural control is an essential function necessary for humans to perform everyday activities, and yet individuals with ASD commonly experience impaired postural control with a negative impact on their mobility at home and in the community. Despite existing research on postural control in individuals with ASD, the mechanisms underlying postural control impairments in this cohort remain unclear. This thesis aims to extend the understanding of the postural control system in individuals with ASD.

This current chapter introduces a brief overview of the postural control system in humans, followed by a literature review on the postural control research in individuals with ASD, and concludes with the aims and structure of this thesis.

1.1 Postural control system in humans

Postural control is a motor skill that enables a person to maintain an upright body posture. It serves two purposes, to stabilize and orientate the body in space (Horak, 2006; Shumway-Cook & Woollacott, 2001). Postural stability describes the maintenance of the center of body mass, which is the point equivalent to the total body mass (Winter, 1995), within the limits of the base of support (Assaiante et al., 2005; Horak, 2006). In contrast, postural orientation describes the alignment of body segments with respect to gravity, the environment, and the internal model of the motor system (Horak, 2006; Massion, 1994). Individuals who have postural control impairments are likely to experience problems with motor control and coordination, report low quality of life in leisure activities and physical capacity, and even falls (Langlois et al., 2012; Tinetti & Kumar, 2010; Wilson et al., 2013).

The work by Horak (2006) has been widely used to frame the postural control system. This framework describes how the postural control system relies on six different resources, comprising of biomechanical constraints, movement strategies, orientation in space, control of dynamics, cognitive processing, and sensory strategies (Horak, 2006). These six resources work interdependently to influence the process of postural control.

The first resource essential for postural control is the biomechanical component of the human body. Biomechanical components, such as the range of joint movement, feet size, and muscle strength, determine the postural stability of an individual (Chiacchiero et al., 2010; Riach & Starkes, 1993; Tomas-Carus et al., 2009). Constraints on biomechanical components could alter the base of support and thus generate a faulty representation of limits of stability, impairing postural control (Horak, 2006).

The second resource important for postural control is the strategies used for movement adjustment. An upright posture has been likened with an inverted pendulum with three main joints (Creath et al., 2005; Suzuki et al., 2012). Each joint is attached to a group of muscles that activates during postural adjustment, contributing to the maintenance of postural stability. These three joint segments use movement strategies known as the ankle strategy, hip strategy, and anticipatory postural strategies (Horak, 2006). The ankle strategy adjusts the center of body mass in response to perturbation by moving the ankle joints (Suzuki et al., 2012). Similarly, the hip strategy adjusts the center of body mass by exerting body movement at the ankle and hip joints to ensure anteroposterior stability (Suzuki et al., 2012). The contribution of the ankle and hip strategies for postural adjustment depends on the size of the base of support (Boonstra et al., 2013). In contrast, the anticipatory postural strategies adjust the center of body mass in response to predictable perturbations by activating the trunk and leg muscles prior to the perturbation (Aruin, 2016; Laessoe & Voigt, 2008). The anticipatory postural strategies use prior experience to prepare the body for the potential effects of the expected perturbation, for example, walking on an uneven ground surface (Kanekar & Aruin, 2014). These movement strategies support the timely adjustment of posture in events of perturbation.

The third resource crucial for postural control is the strategies used for processing and integrating sensory information. Humans receive, process, and combine somatosensory, vestibular, and visual information from the environment to inform their body position in space (Horak, 2006; Peterka, 2002). When there are changes in the environment, the sensory strategies evoke a shift in the contribution of the individual sensory system to adjust the posture of the human body in a process known as sensory reweighting (Assländer & Peterka, 2016; Carver et al., 2006; Horak et al., 1989). For instance, when standing in a well-lit room, the visual system provides the most reliable information and thus has a higher contribution to postural control than the other sensory systems. In contrast, the somatosensory system would provide the most reliable information to a person when standing in a dark room. Therefore, these sensory strategies enable a timely and accurate integration of sensory information for use in the process of postural control.

The fourth resource required for postural control is the capability to orient human body segments in space. Humans use the representation of verticality with respect to gravity as a reference to orientate body segments in an upright position (Barra et al., 2010). The internal model within the central nervous system uses the sensory systems to build knowledge of the body and construct a representation of verticality relative to the environment (Barra et al., 2010; Horak, 2006). Hence, an accurate representation of verticality to gravity gives rise to a stable posture for the execution of daily tasks.

The fifth resource necessary for postural control is the ability for humans to exert control on the center of mass when they experience a change in their base of support. The center of body mass is not within the base of the foot support during tasks like changing of posture or walking. This resource guides the positioning of foot placement to correspond to the center of mass position, enabling a stable control of posture in dynamic tasks (Lugade et al., 2011).

The sixth resource crucial for postural control is the availability of cognitive resources. Cognitive resources, such as attention and learning, provide information to enhance one’s postural control. For example, if sufficient attention is not invested in a person’s postural control when having to read a book while standing on a moving bus, the person may not achieve a stable posture and could fall on the bus (Catena et al., 2011; Siu & Woollacott, 2007). The number of cognitive resources invested in postural control depends on the difficulty of the postural task; a more complex task would require more cognitive resources (Horak, 2006).

1.2 Influence of sensory information on postural control

In addition to the six resources described in the postural control framework by Horak (2006), there are other influences to consider. One of the influences is the sensory information from the environment. Sensory information from the environment is perceived by humans in the form of somatosensory, vestibular, and visual information. Each different type of sensory information provides the central nervous system with details of the environment to generate a posture that meets the demands of the particular environmental context. The influence of sensory information from the environment on postural control has been well-documented (Jeka et al., 2000; Massion, 1994; Peterka, 2002). The following section briefly describes the origin of the sensory information and its influence on postural control.

Somatosensory information in the environment comes mainly from changing positions of the body and through support surfaces (Riemann & Lephart, 2002a, 2002b). As individuals interact with the environment, they pick up tactile information and proprioceptive senses from the muscle spindles, Golgi tendon organs, and joints and cutaneous mechanoreceptors to inform the postural control system of their current body segments in relation to the environment (Riemann & Lephart, 2002a; Shumway-Cook & Woollacott, 2001). However, impairment of somatosensory functions could lead to difficulty with relating body position in space and could result in the display of large postural responses characterized by excessive hip movements and increased hip muscle activation (Horak et al., 1990; Qiu et al., 2012).

Vestibular information comes from head motion in space (Forbes et al., 2015). As the head moves, the semicircular canals and otoliths found in the inner ear of a person sends information about the angular acceleration, linear position, and linear acceleration of the head to the vestibular system (Day & Fitzpatrick, 2005; Forbes et al., 2015). This information supplies the postural control system knowledge on the position of the head and its motion in space relative to gravitational forces (Takakusaki, 2017). In addition, the vestibulospinal pathway sends information regarding the linear and angular head motion to the spinal cord to regulate the muscle tone for postural control (Takakusaki, 2013). Interestingly, people with vestibular loss can still maintain a stable posture if reliable somatosensory and visual information are present because they have sufficient information to estimate the position of their body in space (Mergner et al., 2009). Individuals, who need to compensate for their vestibular loss, tend to rely more on somatosensory information than vestibular information to orientate their body segments to the space in the environment (Peterka et al., 2011).

Visual information comes from the light patterns in the environment. Static and moving light patterns that are received by the retina of the eyes provide the postural control system information about the external objects, events surrounding the person, and the person’s own body movement in relation to the environment (Lee, 1980; Riemann & Lephart, 2002b). Static light patterns supply a fixed visual representation of the environment, supporting a stable posture for the observer. In contrast, moving light patterns (Figure 1.1), known as optic flow fields, supply a changing and uncertain visual representation of the environment (Gibson, 1950; Lee, 1980), creating a sensation of self-motion to the observer (Berthoz et al., 1975; Lappe et al., 1999). This sense of self-motion enables the observer to estimate the direction of heading (Crowell & Banks, 1993; Lappe et al., 1999; Peuskens et al., 2001; Warren & Hannon, 1988) and readjust body alignment to maintain a stable posture (Horiuchi et al., 2017; Lestienne et al., 1977).

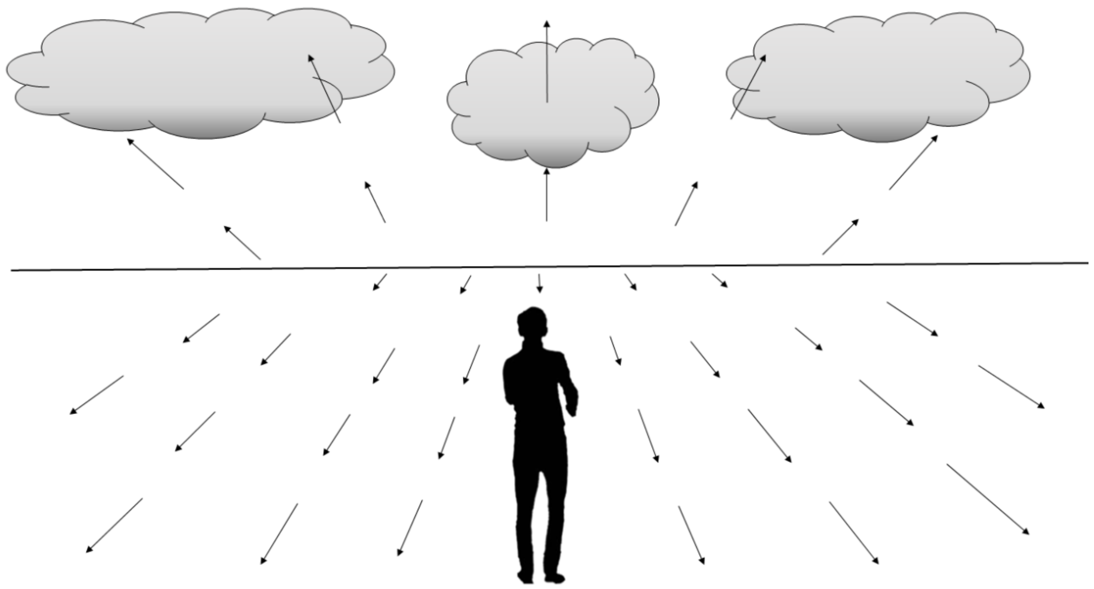

Figure 1.1 Illustration of moving light patterns as indicated by the arrows moving in the direction toward the observer.

1.3 Development of postural control

The ability to maintain an upright body posture develops with time. Across the life span, postural control undergoes refinement and maturation (Adolph & Robinson, 2015). This development of postural control is necessary to support body movements required for the completion of motor tasks at different stages of life (Adolph & Hoch, 2019). Understanding how postural control progresses in childhood through to adulthood helps with the appreciation of postural control in human beings.

The development of postural control in children is usually recognized by the emergence of motor development milestones. These motor milestones consist of a set of observable sequential movements that children are expected to exhibit when they reach a certain age (Adolph & Robinson, 2015). Typically, children are first expected to roll before they can sit, crawl, creep, pull-to-stand, stand independently, and finally walk (Adolph & Robinson, 2015; McGraw, 1932). Researchers have developed two main theories to explain postural development in children, one focused on the reflexes of infants and the other on the maturation process of the postural control system.

The reflex and hierarchical theory of motor control describe reflexes as motor patterns that infants use to activate new patterns of motor behavior; where primitive reflexes are gradually broken down to construct new adaptive motor patterns (McGraw, 1932; Milani-Comparetti & Gidoni, 1967; Schaltenbrand, 1928). Researchers observed the exhibition of various reflexes in infants that tend to emerge and disappear as they developed (McGraw, 1932; Schaltenbrand, 1928), and proposed that these reflexes contribute to the developmental process of postural control (Magnus, 1926). However, the usefulness of this theory in explaining postural development beyond infancy is debatable (Campbell & Wilhelm, 1985; Cano-de-la-Cuerda et al., 2015).

The theory concerning the maturation process of the postural control system describes that the postural control system develops simultaneously with the maturation of biological processes in the central nervous system (Assaiante et al., 2005; Horak, 2006; Shumway-Cook & Woollacott, 2001). An example of a biological process that matures alongside the postural control system is the sensory system. The somatosensory system matures at around five to 10 years of age and the vestibular and visual systems mature between 15 and 16 years of age (Cumberworth et al., 2007; Sá et al., 2018; Steindl et al., 2006). Therefore, adult-like postural control occurs at the age when the human's sensory systems are fully developed (Verbecque et al., 2016). It is important to note that static postural control matures at a faster rate than dynamic control (Assaiante et al., 2005; Gouleme et al., 2014; Hong et al., 2008). Another emphasis of the theory is on learning through experience. Sensory-motor maps are developed through experiences of human movement in a gravity environment (Medina & Coslett, 2010; Shumway-Cook & Woollacott, 2001). Hadders-Algra et al. (1996) found that the restoration of postural stability in infants was faster after they underwent a postural control intervention that incorporated varied sensory conditions, suggesting that repeated exposures to different sensory experiences can enhance postural control development (Hadders-Algra et al., 1996). It is important to note that the postural control system, learning experience, and growth rate of each child is unique; hence, the postural control development of each child can vary (Dusing & Harbourne, 2010; Riach & Hayes, 1987).

1.4 Consequences of postural control impairments on individuals

Aberrant postural control can impact on a person's health and functioning. A helpful approach to envisage the consequences is by the use of the International Classification of Functioning, Disability, and Health (ICF) framework developed by the World Health Organization (WHO). The ICF framework is based on a biopsychosocial model that describes health and functioning from the perspective of biological, individual, and social components (World Health Organization, 2001). The framework illustrated in Figure 1.2 shows the interconnections between the health condition, three levels of human functioning, and contextual factors of the person. Within the three levels of human functioning are the body functions and structure, activity execution, and participation in life situations. The contextual factors comprise of external environmental factors and internal personal factors. An occurrence of dysfunction at any one or more of these components influences the functioning of a person at three possible levels: body function impairment, activity limitation, and participation restriction.

Postural control impairments can influence a person's activity execution and participation in life situations. At the body function level, individuals with impaired postural control could experience motor coordination deficits (Burns et al., 2009; Flatters et al., 2014; Haddad et al., 2013). Consequently, individuals experiencing motor coordination deficits could face challenges in activities, such as reaching out for objects, self-care, and mobility tasks (Curtis et al., 2015; Pavao et al., 2013; Pavão et al., 2014). Pavão et al. (2014) found that children with poorer postural control outcomes required more assistance from their caregivers with self-care tasks that involved standing, such as bathing, changing clothes, and toileting. This group of individuals tends to rely more on their caregivers to assist them in daily tasks and experiences participation restriction in relation to school readiness, and community and sporting engagements (MacDonald et al., 2018; Vandorpe et al., 2012). In particular, participation in community engagements would be even more difficult in the presence of physical barriers in the environment, for instance, in places with several flights of stairs (Layton, 2012). Therefore, postural control impairments can have far-reaching consequences on the individual, and thus new insights into postural control are important to inspire novel interventions and methods of assessment in future research.

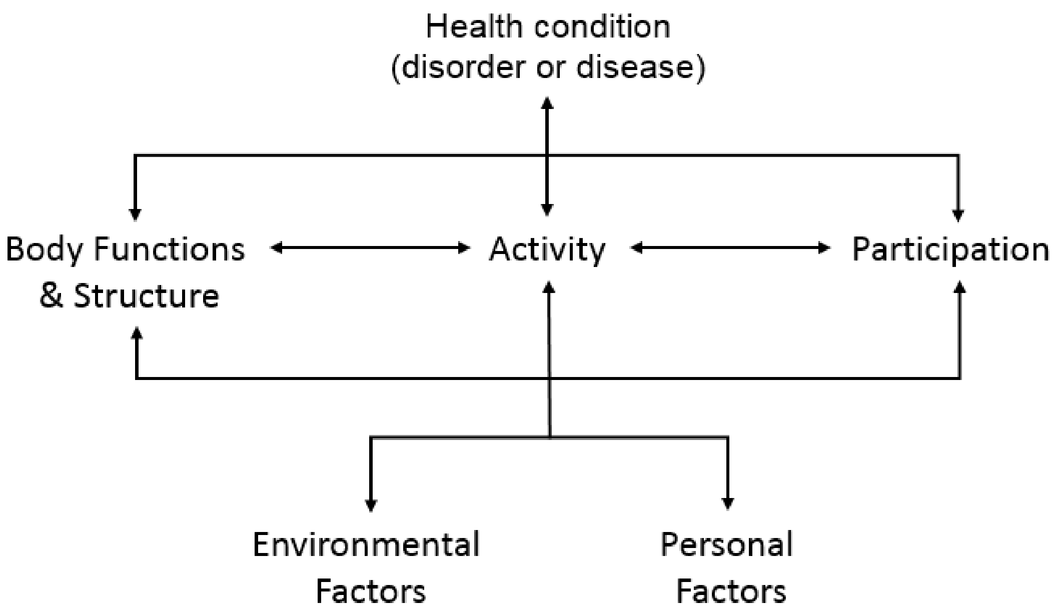

Figure 1.2 Diagram of the interconnections between the components of the ICF. Adapted from "*International classification of functioning, disability, and health*" by the World Health Organization, 2001. Copyright 2001 by the World Health Organization.

1.5 Autism spectrum disorder and postural control impairment

Autism spectrum disorder (ASD) represents a heterogeneous group of neurodevelopmental disorders, characterized by difficulties in social interactions and productive communication, with the exhibition of restricted and repetitive patterns of behavior or interests (American Psychiatric Association, 2015; World Health Organisation, 2013). Additionally, individuals with ASD experience mobility issues. In a national health survey conducted in 2015, an approximated 85,280 Australians with ASD have indicated facing profound or severe mobility limitations (Australia Institute of Health and Welfare, 2017). Three in ten of those individuals have indicated needing help from their caregivers at least once a day in aspects of mobility, such as walking a short distance, climbing stairs, bending down to pick up an object from the ground, and using public transportation (Australia Bureau of Statistics, 2017).

There is a substantial body of literature on mobility issues in individuals with ASD. Many of them have been found to display a gait pattern that is clumsy and uncoordinated (Asperger, 1991; Ghaziuddin & Butler, 1998; Kanner, 1943). Children and adults with ASD alike have been reported to exhibit a different gait pattern than typically developing/developed (TD) controls in terms of smoothness of movement, cadence, step length, and stride length (Calhoun et al., 2011; Hallett et al., 1993; Rinehart et al., 2006; Weiss et al., 2013). Previous studies have suggested postural control impairments, proprioceptive processing disruption, and behavioral anxiety as causes of mobility issues in individuals with ASD (Fournier et al., 2010; Kindregan et al., 2015).

Several studies have examined postural control in individuals with ASD to understand how postural control impairments could affect the mobility in this cohort (Ament et al., 2015; Fournier et al., 2010; Vernazza-Martin et al., 2005); however, the evidence of postural control impairments in ASD is not clear. For example, some studies have reported a more unstable posture in individuals with ASD relative to TD individuals (Ament et al., 2015; Downey & Rapport, 2012; Memari et al., 2014). In contrast, other studies have reported no difference in postural stability between individuals with ASD and TD individuals (Greffou et al., 2012; Travers et al., 2013). It is necessary to note that many of the studies used different measurement tools to assess postural control in ASD (Molloy et al., 2003; Whyatt & Craig, 2012), for instance, standardized motor function assessment and instrumental devices, such as force platform. Nonetheless, the findings have been inconsistent and thus limit the knowledge of postural control in ASD.

In addition to a limited understanding of postural control in individuals with ASD, many researchers have different perspectives when it comes to explaining the mechanisms underlying postural control impairments in ASD. Minshew et al. (2004) have suggested that abnormal sensory-motor brain network connectivity could underlie postural control impairments in ASD. In contrast, Doumas et al. (2016) have suggested an implication of the cerebellum in the impairment of postural control in ASD. Furthermore, Morris et al. (2015) have suggested that postural control impairments could be due to problems with the vision-for-action pathway of individuals with ASD. In considering the importance of postural control in gait and mobility (Pirker & Katzenschlager, 2017), there is a need for a clearer understanding of the postural control system in individuals with ASD as it has implications on the development of postural control intervention for this cohort.

Given a lack of clarity in the knowledge of the postural control system in individuals with ASD, researchers have approached the development of postural control interventions for this cohort differently. Some have adapted sports routines commonly used by TD individuals to improve their posture for children with ASD, like swimming (Yilmaz et al., 2004) and Korean martial arts (Kim et al., 2016), while others have employed specialized training, such as horseback riding programs (Silkwood-Sherer et al., 2012; Wuang et al., 2010), postural control intervention performed under varying sensory conditions (Cheldavi et al., 2014), and real-time visual feedback intervention (Somogyi et al., 2016) to improve postural control in children with ASD.

Despite the wide variety of postural control interventions available in the literature, it is not certain how these interventions could ameliorate postural control without first understanding the mechanisms underlying postural control impairments in individuals with ASD. Therefore, further knowledge of the postural control system in individuals with ASD is necessary.

Using the framework by Horak (2006), the present thesis explores the postural control system in ASD through understanding the influence of sensory information on postural control. The reason to focus on the sensory component of the framework stems from numerous evidence of sensory processing difficulties in individuals with ASD. Several studies have found children with ASD displaying behaviors that reflect either increased or decreased sensitivity to sensory information from the environment (Ashburner et al., 2008; Ben-Sasson et al., 2009; Germani et al., 2014; Tomchek & Dunn, 2007; Van Etten et al., 2017). In particular, researchers have found that individuals with ASD process visual information differently from TD individuals. Individuals with ASD tend to be more skillful in recognizing hidden figures and searching for novel targets (Horlin et al., 2016; Kaldy et al., 2011; Mottron et al., 2006; O'Riordan M, 2004) but have difficulties making sense of facial expressions and emotions of others in comparison with TD controls (Falkmer et al., 2011; Simmons et al., 2009). Furthermore, they struggle with visual tasks, such as identifying directions of moving stimulus in psychophysical tests and detecting human motion (Kaiser & Shiffrar, 2009; Milne et al., 2002; Sutherland & Crewther, 2010). Gepner and Mestre (2002) suggested that the synchronization between moving visual information and postural responsiveness could be weak, resulting in impaired postural control when children with ASD process visual information for postural control. This atypical postural response to moving visual information has been speculated to be an issue of the magnocellular pathway (Gepner & Mestre, 2002).

There is evidence of magnocellular pathway impairment in individuals with ASD (Burt et al., 2017; Greenaway et al., 2013; Thompson et al., 2015). The magnocellular pathway is a transmission pathway in the visual system of the brain that serves to send visual information comprising of motion and low spatial frequency from the occipital lobe to the posterior parietal cortex, a region of the brain involved in sensorimotor processing (Goswami, 2015; Milne et al., 2002; Parrish et al., 2005). Individuals with ASD and TD individuals have been found to respond differently in psychometric and psychophysical tests designed to assess magnocellular functioning (Burt et al., 2017; Greenaway et al., 2013; McCleery et al., 2007; Milne et al., 2002; Sutherland & Crewther, 2010). Compared with TD children, children with ASD showed a higher luminance contrast threshold on the steady pedestal-paradigm, reflecting the presence of magnocellular function impairment (Greenaway et al., 2013). Adults with ASD also showed lower brain signal activation than TD controls during a facial expression task designed to elevated brain signals associated with magnocellular processing (Burt et al., 2017). In addition, the magnocellular pathway is implicated in processing two important sources of visual information needed for postural control: optic flow information and information presented in the peripheral visual field (Bayle et al., 2011; Browning et al., 2009). Therefore, further investigation of visual information impact on postural control could provide new insights into the mechanisms underlying postural control in ASD.

1.6 Gaps in research

At present, findings relating to the influence of visual information on postural control in individuals with ASD have been unclear. Some studies have found that individuals with ASD display a larger postural response than the controls when visual information in the environment is incongruent (Price et al., 2012), while other studies found no difference in postural responses between the groups (Gepner & Mestre, 2002; Greffou et al., 2012). In contrast, a number of studies have reported a larger postural response in individuals with ASD than in TD individuals when they stand while looking at a target (Chen & Tsai, 2015; Kohen-Raz et al., 1992). Furthermore, the study by Molloy et al. (2003) found a larger postural response in the ASD group than the controls when they stand with their eyes closed, but there was no group difference when they stand with their eyes opened. The inconsistencies in findings could be due to various differences in research methodology relating to the assessment of postural control in individuals with ASD. Hence, four gaps in research have been identified and discussed in the following section.

1.6.1 Limited studies with real-world applicability

The first gap in research relates to the limited postural control studies in ASD with real-world applications. Studies in ASD research often employed conventional methods, such as a static target or a 2-dimensional moving object as visual stimuli, to assess the influence of visual information on postural control (Fournier et al., 2010; Gepner & Mestre, 2002; Molloy et al., 2003). However, findings from these studies might not be relevant to interpret postural control in individuals with ASD in real-life scenarios (Ding et al., 2012; Shuchat et al., 2012). Only a handful of studies, such as Greffou et al. (2012) and Price et al. (2012), have used virtual reality technology to create and project ecologically valid visual motion stimuli, for example, a moving tunnel paradigm and a dynamic scene of a school walkway, to assess postural control in individuals with ASD. Through these studies, novel insights relating to possible mechanisms underlying poor postural control in individuals with ASD have been revealed. These include the postulation of abnormal connectivity of the visuo-cerebellar circuits in the ASD cohort that impairs the transmission of visual motion information to the postural control system (Greffou et al., 2012).

The employment of naturalistic visual stimuli in a controlled laboratory environment to understand how people react in the real world is not a new concept. Previously, Lee and Aronson (1974) have used the moving room paradigm to create optic flow illusions of varying directions to understand how people respond to optic flow fields in the real world. The forward movement of the room created optic flow fields that moved toward the observer and induced a backward movement in the observer who would instantly adjust his/her posture to move forward to counteract the initial backward movement of the body (Lee & Aronson, 1974). Likewise, the room when moved backward created optic flow fields that moved away from the observer and induced a forward movement in the observer who would adjust his/her posture to move backward to counteract the initial forward movement of the body. The study demonstrated two optic flow fields commonly observed in the natural environment: optic flow fields that move toward and away from the observer (Lee & Aronson, 1974). This directional specific postural responsiveness to varying directions of optic flow fields demonstrated the sensitivity of the postural system to visual environmental influences. While the moving room paradigm has proven to be a useful approach to understand the influence of optic flow on postural control and has been used by subsequent studies (Barela et al., 2009; Godoi & Barela, 2016; Stoffregen, 1985; Wade et al., 1995), its setup could be considered cumbersome as it requires the construction of large walls and ceiling. However, the advancement of virtual reality technology has provided a more accessible way to construct immersive and interactive environments that match the real-world environment through various sensory interfaces (Miller et al., 2019; Piponnier et al., 2009; Shuchat et al., 2012). Therefore, it would be valuable to use an ecologically valid approach in the investigation of postural control to uncover new insights into mechanisms underlying postural control in individuals with ASD.

1.6.2 Limitation on the field of vision in postural control assessment

The second gap in research relates to the field of vision used in postural control assessments. Traditionally, the field of the vision in postural control assessment in ASD research has been confined to the central visual field. Numerous studies have described the assessment of postural control in combination with a visual fixation on a point or a target located in the center of the participant’s field of view (Bucci et al., 2013; Chen & Tsai, 2015; Doumas et al., 2016; Memari et al., 2013). The procedures used in those studies disregarded the fact that the human’s vision consists of both the central and peripheral visual fields (Figure 1.3). The central visual field covers an area within 10º from the center of the visual field while the peripheral visual field covers the area surrounding the central visual field (Lawrence et al., 2006; Nougier et al., 1997). Visual information perceived at each visual field influence postural control differently. The radial flow fields (Figure 1.4) in which the central visual field mostly receives move radially along flow lines from the center of projection and is used to guide one's postural orientation (Piponnier et al., 2009; Wade & Jones, 1997). In contrast, the lamellar flow field (Figure 1.4) that the peripheral visual field receives flow parallel to the line of motion and is used to adjust human's postural equilibrium (Piponnier et al., 2009; Wade & Jones, 1997). Studies have found that lamellar flow fields induced a larger postural response in observers compared to radial flow fields (Piponnier et al., 2009; Stoffregen, 1985; Wade et al., 1995), suggesting that visual information received in the peripheral visual field has a major contribution to the control of posture (Cohen & Haith, 1977; Lestienne et al., 1977; Piponnier et al., 2009). If the information in the peripheral visual field underpins postural control, accurate visual processing of peripheral vision is important for postural control.

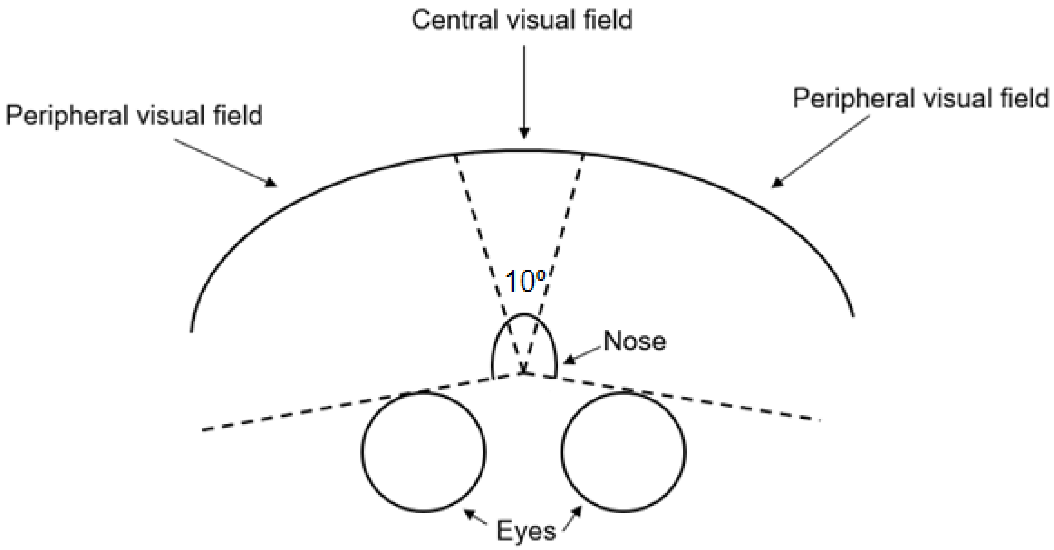

Figure 1.3 Illustration of the central and peripheral visual fields from the view from the top of the head. Adapted from "*Eye Anatomy and Function*" by Murray (n.a.), University of Washington. Retrieved August 3, 2019 from https://faculty.washington.edu/chudler/eyetr.html.

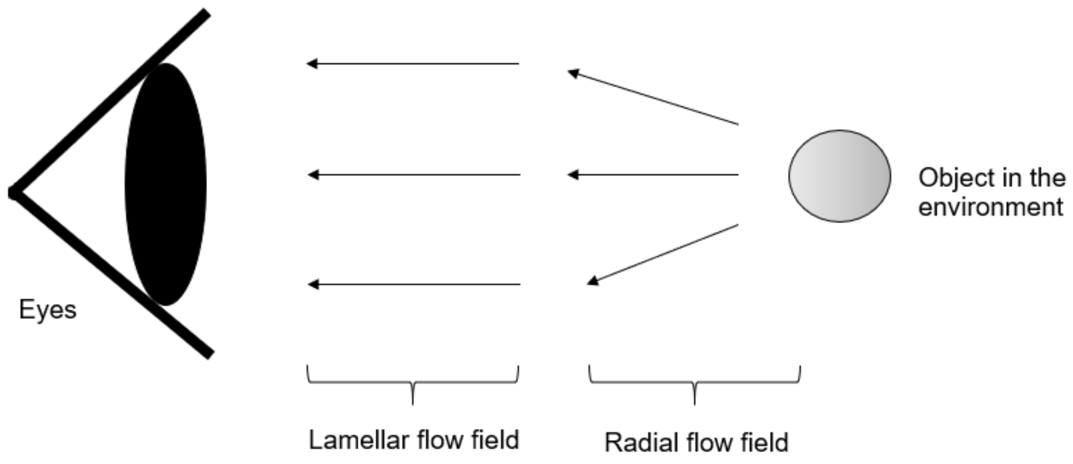

Figure 1.4 Illustration of the radial and lamellar flow fields reflecting into human's eyes.

While accurate peripheral vision is essential for postural control, visual processing of peripheral vision in children with ASD tends to be different from TD children. Children with ASD have been found to demonstrate less accuracy in detecting light targets shown in the peripheral visual field (Milne et al., 2013) and have a higher brain activity level than TD controls when lights were presented in the peripheral visual field (Frey et al., 2013). The brain activity level was comparable between children with ASD and TD children when lights were presented in the central visual field (Frey et al., 2013). It is not clear if this different processing of peripheral vision affects the postural control in ASD. Given the importance of peripheral vision to postural control (Cohen & Haith, 1977; Lestienne et al., 1977; Piponnier et al., 2009), it is necessary to expand the field of vision in postural control assessment to include both the central and peripheral visual fields in order to understand how information from the two different visual fields could influence postural control in individuals with ASD.

1.6.3 Sparse postural control studies involving both children and adults with autism spectrum disorder

The third gap in research relates to the proportion of postural control studies in children and adults with ASD. Currently, the number of studies examining standing postural control in children with ASD is disproportionally larger than the number of studies in adults with ASD (Morris et al., 2015). This research trend places a limitation on understanding postural control development across the ASD lifespan. Knowledge of postural control in both childhood and adulthood is essential because it provides knowledge on the development of postural control over time (Adolph & Robinson, 2015). A landmark study by Minshew et al. (2004) examined postural control in both children and adults with ASD and found that postural control development in ASD is unlike that of TD children and adults. Minshew and colleagues (2004) found that while TD children show a linear progression in the development of postural control, postural control development appeared to be delayed in children with ASD. In addition, postural control in ASD does not mature into the adult-level (Minshew et al., 2004). The finding of atypical postural control development in ASD was possible because of the inclusion of children and adults with ASD in the prior study. However, there is a scarcity of studies on postural control in adults with ASD, with even fewer studies on postural control in both children and adults. Thus, there is a limited understanding of postural control development across the ASD lifespan.

1.6.4 Lack of a theoretical framework in the autism spectrum disorder postural control literature

The fourth gap in research relates to the lack of a theoretical framework in the ASD literature. A framework provides a systematic approach for the analysis and interpretation of research findings (Schoneburg et al., 2013; Sibley et al., 2015). Although frameworks are often used to understand postural control in various fields of research, it is not common in ASD research. One of the frameworks that researchers have used to extend the understanding of sensorimotor control in humans, an aspect of postural control, is the optimal feedback control framework (Benyamini & Zacksenhouse, 2015; McNamee & Wolpert, 2019; Wolpert, 1997; Wolpert & Flanagan, 2016). The optimal feedback control framework provides a structured approach to examine the mechanisms underlying the sensorimotor control system in human beings (Körding & Wolpert, 2006; Todorov, 2004;

Wolpert et al., 2011). The sensorimotor control system often faces challenges with the transmission of information within the central nervous system (Franklin & Wolpert, 2011; Kawato et al., 1987). During information transmission, several issues could arise, for example, noise in sensory information from the environment and delays in transmission of sensory information (Franklin & Wolpert, 2011; Kawato et al., 1987; Wolpert, 1997). Thus, the framework is used to identify and resolve challenges in various components within the sensorimotor control system, such as the human operator, sensory systems, state estimator, and optimal feedback controller (Fernández-Cara & Zuazua, 2003; Todorov, 2007) (Figure 1.5). Details of the optimal feedback control framework proposed by Todorov (2004) are described as follows.

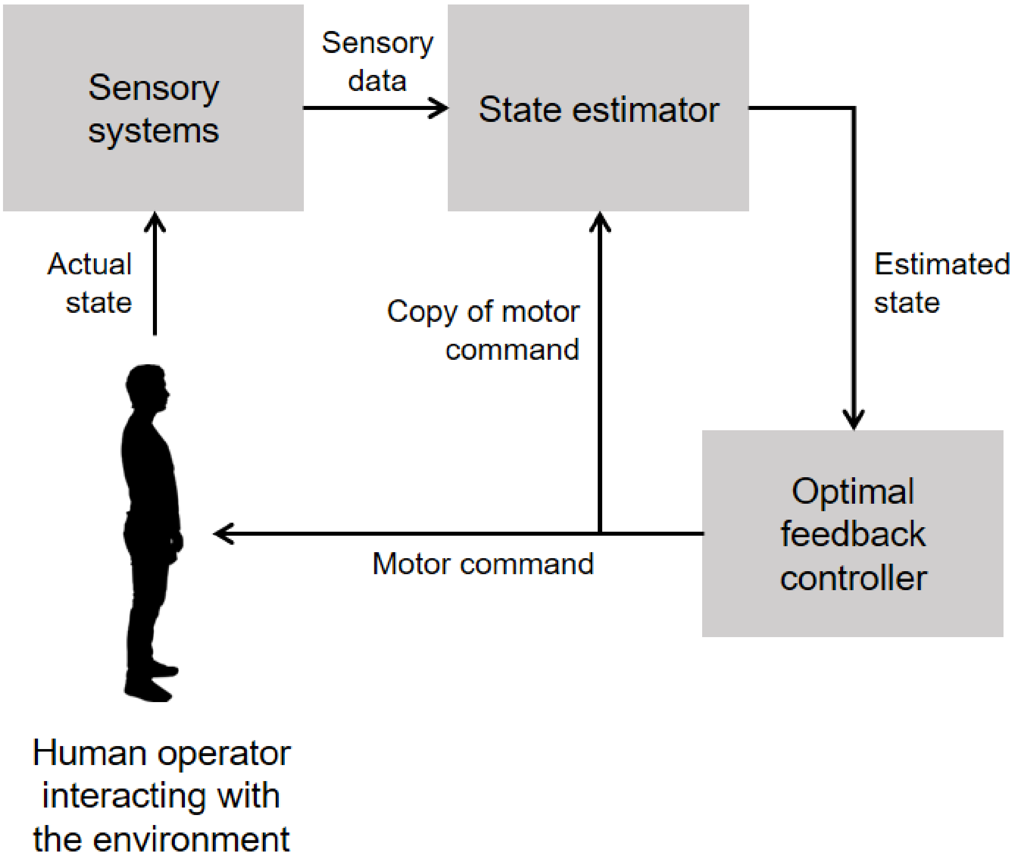

Figure 1.5 Diagram of the optimal feedback control framework of the sensorimotor control system. Adapted from "*Optimality principles in sensorimotor control (review)*" by E. Todorov 2004, Nature Neuroscience, 7(9), p.15. Copyright by Springer Nature Publishing AG.

The human operator (person) represents the state of the body that interacts with the external environment (Diedrichsen et al., 2010; Todorov, 2004). Information concerning the person's body, for example, the joint angles, body movement, and body position in relation to relevant objects are used to construct the actual state of the person in the sensorimotor control system (Todorov, 2004). The actual state of the person commences the information transmission within the sensorimotor control system.

The next component is the sensory systems. The different sensory systems process somatosensory, vestibular, and visual information to inform the actual state of the person (Orbán & Wolpert, 2011; Peterka, 2002; Todorov, 2004). Some challenges that could arise during the reception and processing of sensory information include sensory noise and time delays during transmission (Todorov, 2004).

Sensory information that has been processed is sent to the state estimator. The state estimator constructs an internal representation of the state of the body in relation to the environment from incoming sensory information and prior estimations (Diedrichsen et al., 2010; Wolpert, 1997). The prior estimations comprise a copy of the motor command that was produced previously in the sensorimotor control system (Benyamini & Zacksenhouse, 2015; Wolpert, 1997; Wolpert et al., 1995). Some challenges that could arise within this component include delays in sensory information transmission and problems with the integration of sensory and motor information (Benyamini & Zacksenhouse, 2015; McNamee & Wolpert, 2019).

Subsequently, the estimated state of the person is carried to the optimal feedback controller. The optimal feedback controller depends on the state estimates to determine the motor commands for the accomplishment of tasks presented to the person (Benyamini & Zacksenhouse, 2015; McNamee & Wolpert, 2019; Todorov, 2004; Wolpert & Kawato, 1998). The motor commands are then forwarded to the person's musculoskeletal components for motor execution. Simultaneously, a copy of the command is forwarded to the state estimator as a predictor of upcoming movement (McNamee & Wolpert, 2019; Wolpert & Flanagan, 2001; Wolpert et al., 1995). Some challenges that could arise within this component include sensory noise and errors introduced by sensorimotor delays (Todorov, 2004).

The continuous processes that occur in the sensorimotor control system underpin the construction of the internal model of postural control. An internal model reflects a presentation of a person's body or environment within the central nervous system (Flanagan & Wing, 1997; McNamee & Wolpert, 2019; Wolpert et al., 1995). It allows the person to construct predictive models of the sensory environment through learned experience to guide motor behaviors that are robust and flexible (McNamee & Wolpert, 2019; Wolpert & Kawato, 1998).

To put the optimal feedback control framework of the sensorimotor control system into context, the following example will describe the processes involved in the task of quiet standing. As a person interacts with the environment, the sensory systems pick up sensory information from the environment in relation to the person. This information informs the actual state of the person. Somatosensory, vestibular, and visual information is sent to the state estimator for integration, forming an estimated state of the person. The estimated state of the person is carried to the optimal feedback controller for motor planning. The optimal feedback controller produces motor commands appropriate for the completion of quiet standing. Thereafter, the motor commands are sent to the related musculoskeletal components for motor execution. A copy of the command goes back to the state estimator and serves as a predictor for upcoming body movement.

Overall, the framework breaks down the processes of information transmission in the sensorimotor control system, providing a structured approach to identifying possible challenges in the production of controlled body movement in individuals with ASD. A similar framework has been used to explain the motor abilities in ASD elsewhere (Gowen & Hamilton, 2013). Therefore, the analysis and interpretation of research findings using the optimal feedback control framework could inspire novel insights into the postural control system of ASD.

1.7 Significance of the thesis

The study of postural control in ASD is important because the number of individuals with ASD who face mobility issues is expected to increase in the years to come (Australia Institute of Health and Welfare, 2017). Consequently, the issues of mobility in individuals with ASD are likely to intensify alongside the increasing burden of mobility assistance to these individuals by formal and informal support services (Vohra et al., 2014). A prerequisite to tackle mobility issues is a sound knowledge of the postural control system in ASD. However, at present, knowledge of the postural control system in individuals with ASD remains unclear. The present thesis aims to make a significant contribution to the literature through extending the understanding of the postural control system in individuals with ASD with a particular focus on the influence of visual information on postural control using a variety of research methods.

Findings from this thesis could benefit three groups of people. For the research community, the findings could close the gaps in current research and provide new knowledge relating to the postural control system and mechanisms underlying postural control impairments in individuals with ASD. For clinicians, the findings could be useful to guide the development of postural control interventions to improve postural control and subsequently mobility in the ASD cohort. For the wider community, the findings could inform individuals with ASD about the factors that contribute to their mobility issues.

1.8 Aim of the thesis

The aim of the thesis was to extend the understanding of the postural control system in the ASD cohort. Consequently, the research objectives of the thesis were to:

1. Examine the effect of sensory information on postural control between individuals with ASD and TD individuals, and

2. Examine the effect of visual information on postural control in children and adults with ASD in relation to TD children and adults.

1.9 Overview of the thesis structure

This thesis is presented in eight chapters with a reference list attached at the back of every chapter. Chapter 1 of this thesis, which is the current introduction chapter, along with Chapters 2 and 8 are presented in a traditional thesis format. Chapters 3, 4, 5, 6, and 7 are presented in the format of a scientific journal article and have been published in peer-reviewed journals. The format and referencing style of the published chapters vary accordingly to the individual journal guidelines. Overall, American spelling and the American Psychological Association referencing system are used throughout the thesis.

Chapter 2 introduces the research methodology used in this thesis. This includes details and rationales for the research design, ethical approval and considerations, data collection procedure, and statistical analyses of the studies. This chapter describes the theoretical underpinning for the studies undertaken in this thesis.

Chapter 3 contains a systematic review that summarized the literature relating to postural control in individuals with ASD under various sensory conditions. The systematic review used two analytical approaches – a meta-analysis and narrative synthesis – to compare the effect of sensory information on postural control between individuals with ASD and TD individuals. The results from the systematic review provided evidence regarding postural control impairments in the ASD cohort. In addition, the results provided a basis for exploring the effect of visual information on postural control in the subsequent chapters of the current thesis. The systematic review has been published in Lim, Y. H., Partridge, K., Girdler, S., & Morris, S. L. (2017). Standing postural control in individuals with autism spectrum disorder: Systematic review and meta-analysis. *Journal of Autism and Developmental Disorders, 47*(7), 2238-2253. https://doi.org/10.1007/s10803-017-3144-y.

Chapter 4 comprises the first of the four studies that detailed the investigation of how children and adults with ASD use visual information to control their posture. The study used an experimental study design to evaluate the effect of static visual information on postural control between adults with ASD and TD adults. Specifically, the assessment of quiet standing was conducted under two conditions, eyes open and eyes closed. Extended knowledge regarding the influence of static visual information on postural control in adults with ASD can be found in this chapter. The experimental study has been published in Lim, Y. H., Lee, H. C., Falkmer, T., Allison, G. T., Tan, T., Lee, W. L., & Morris, S. L. (2019). Effect of visual information on postural control in adults with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 49*(12), 4731-4739. https://doi.org/10.1007/s10803-018-3634-6.

Chapter 5 continues with the second of the four-study series on the exploration of visual information usage for postural control in children and adults with ASD. The study in this chapter employed an experimental study design to examine the effect of static visual information on postural control in children with ASD and TD children. Children with ASD and the controls underwent quiet standing while looking at a static target or closing their eyes. The chapter includes discussions on the developmental progression of postural control in individuals with ASD. The experimental study has been published in Lim, Y. H., Lee, H. C., Falkmer, T., Allison, G. T., Tan, T., Lee, W. L., & Morris, S. L. (2019). Effect of visual information on postural control in children with autism spectrum disorder. *Journal of Autism and Developmental Disorders*. https://doi.org/10.1007/s10803-019- 04182-y.

Chapter 6 comprises the third study in the series of four studies looking at postural control of children and adults with ASD in response to optic flow. The experimental study in this chapter evaluated the postural responses to optic flow stimulation in children and adults with ASD in comparison to TD children and adults using optic flow fields that were designed to flow in various directions to reflect the changing light pattern in ecologically valid environments. Furthermore, the study examined the effect of visual field dimension and age on postural responses of children and adults with ASD. The chapter closes with a discussion on the possible neural mechanisms that could underlie postural control impairments in individuals with ASD. The experimental study has been published in Lim, Y. H., Lee, H. C., Falkmer, T., Allison, G. T., Tan, T., Lee, W. L., & Morris, S. L. (2018). Effect of optic flow on postural control in children and adults with autism spectrum disorder. *Neuroscience, 393*, 138-149. https://doi.org/10.1016/j.neuroscience.2018.09.047.

Chapter 7, the last of the four-part study series, analyzed the function of time in relation to the use of optic flow to control body posture in children and adults with ASD. The study is a secondary analysis of the study in Chapter 6, focusing on the evaluation of the amount of time taken to restore postural stability and the amount of change in postural response between repeated trials of optic flow stimulation. These analyses revealed insights into the sensorimotor process and postural control development of individuals with ASD. The conclusion of the chapter includes a proposal for further investigation into the sensory reweighting process of individuals with ASD in the continuous search for the underlying mechanisms of postural control impairments in the ASD cohort. The experimental study has been published in Lim, Y. H., Lee, H. C., Falkmer, T., Allison, G. T., Tan, T., Lee, W. L., & Morris, S. L. (2019). Postural control adaptation to optic flow in children and adults with autism spectrum disorder. *Gait & Posture, 72*, 175-181. https://doi.org/10.1016/j.gaitpost.2019.06.007.

Chapter 8 presents the general discussion of the thesis, strengths and limitations of the thesis, and recommendations for future research.

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Chapter 2 Research Methodology

This chapter outlines the research methodology of the studies in the thesis. It comprises details and rationales for the research design, ethical approval and considerations, data collection procedure, and statistical analyses of the studies.

2.1 Systematic review

A systematic review was designed to summarize and integrate research evidence in relation to the effect of sensory information on postural control in individuals with autism spectrum disorder (ASD) and typically developing/developed (TD) individuals. The review, reported in Chapter 3 of the thesis, employed a search strategy with the medical subject heading terms relating to “autism spectrum disorder” and “postural control” in five electronic databases to ensure that most of the published articles would be encapsulated in the review.

2.1.1 Inclusion criteria and quality assessment of studies

Four main criteria were predetermined to ensure the inclusion of relevant articles reporting on research evidence in relation to the effect of sensory information on postural control in individuals with ASD in the review. The articles were required:

i. To compare postural control of individuals with ASD and TD individuals. TD individuals would serve as controls to compare the difference in postural responses between individuals with ASD and TD.

ii. To examine postural control using a static bipedal stance. Having a stable static bipedal stance is important for initiating complex postural tasks, such as walking (Pirker & Katzenschlager, 2017). Although static bipedal stance is a relatively simple task to examine in children and adults with ASD, it can be inherently unstable (Ivanenko & Gurfinkel, 2018). Therefore, the static bipedal stance is a suitable procedure to examine the postural control function.

iii. To assess static bipedal stance using instrumental measurements. Instrumental measurements provide an objective and quantifiable method of assessing postural control (Paillard & Noe, 2015). Studies with instrumental measurement could supply a more accurate measure of postural control compared to the gross measure of postural control from standardized motor function assessments (Paillard & Noe, 2015).

iv. To investigate postural control in conjunction with one or more sensory stimuli. The assessment of postural control under various sensory conditions would provide information on the influence of sensory information on postural control in individuals with ASD.

In addition to the inclusion criteria, the 'Standard Quality Assessment Criteria for Evaluating Primary Research Papers from a Variety of Fields', a quality assessment tool developed by the Alberta Heritage Foundation for Medical Research (Kmet et al., 2004) was chosen to assess the quality of the studies included in the systematic review. The assessment tool could be applied to assess the quality of research studies with different research designs. Two independent reviewers were designated to assess the quality of the eligible studies to eliminate bias.

2.1.2 Data synthesis and analysis

The data in the systematic review were categorized and synthesized based on the sensory condition used in the study. In each sensory condition, two methods of data analysis were used: narrative synthesis and meta-analysis. A narrative synthesis was used to describe the characteristics of the studies and to report the synthesized findings from studies that did not provide quantitative data. The meta-analysis was used to synthesize quantitative data because the eligible articles were sufficiently homogenous in terms of participants, interventions, and outcomes.

2.2 Experimental studies

Four experimental studies were designed to assess postural control of participants with ASD and their matched TD controls in various visual conditions (Refer to Chapters 4, 5, 6, and 7). Different visual conditions were employed in the studies to understand the effect of visual information on postural control in children and adults with ASD in relation to TD children and adults.

2.2.1 Inclusion criteria and recruitment of participants

Seven specific criteria were predetermined to ensure the selection of suitable participants in the study. The participants were required:

i. To have a normal or corrected-to-normal vision. This was important as visual acuity has been found to alter postural control (Mohapatra et al., 2012). Self- or caregiver-report of visual acuity was deemed sufficient.

ii. To be between 8 and 12 years old or between 18 and 50 years old. Child participants between 8 and 12 years old were selected because children within this age range have been reported to show similar capability in using visual information for postural control (Sparto et al., 2006). Furthermore, adult-like postural control is not found in children before the age of 13 years old (Verbecque et al., 2016). In addition, adult participants were limited to the age of 50 years old to reduce the effect of age on postural control as it is recognized that adults aged 65 years and above tend to be at high risk of falls (World Health Organisation, 2018).

iii. To comprehend English. This was because the accuracy of the study results depended on the ability of the participants to adhere to the study procedures.

iv. To stand independently for short periods. This was necessary for accurate measurement of postural control with static bipedal stance.

v. To have no history of seizure or epilepsy. This was to prevent harm to participants as some of the visual conditions were designed to cause self-motion. The fast-moving light patterns in some visual conditions might have the potential to provoke a seizure and thus not suitable to be used on participants with a history of seizure or epilepsy (Ferlisi & Shorvon, 2014).

vi. (In the case group) To have a clinical diagnosis of ASD or Asperger's syndrome, or pervasive developmental disorder not otherwise specified as determined by a multidisciplinary team, consisting of a physician, psychologist, and speech pathologist.Participants on medication were not excluded – six participants with ASD took stimulant medication and five participants took antidepressant medication for treatment of anxiety for at least three months.

vii. (In the control group) To have no co-morbidities that could affect the completion of the static bipedal stance and have no siblings with ASD. This criterion was established to reduce the risk of contamination of the control group, as studies have reported that the person with a sibling with ASD has a higher risk of ASD diagnosis that may not have been discovered at the time of the study (Tick et al., 2016). None of the participants in the control group took medication.

Participants in the case and control groups were purposively recruited. Participants in the ASD group were recruited through email and phone contacts. In contrast, those in the control group were recruited through advertising flyers, social media platforms, and by word of mouth.

2.2.2 Ethical approval and considerations

The Curtin University Human Research Ethics Committee (HREC) approved the experimental studies, approval number: HR 28/2016 (Refer to Appendix C). All of the experimental studies were designed to conform to the requirements stated in the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) (National Health and Medical Research Council, 2018) and the Declaration of Helsinki 2013 (World Medical Association, 2019). Annual reports were provided regularly to the Curtin University HREC to maintain the research ethics approval.

Participants and caregivers of participants between 8 and 12 years old were informed about the study prior to giving assent or consent for participation. Information about the study included the purpose and the benefits of the research, responsibilities of the participants, foreseeable risks when partaking in the study, and the voluntary nature of participation in which participants have the right to withdraw at any time without incurring any adverse consequences (Refer to Appendix D). Participants and caregivers were offered the opportunity to clarify anything relating to the study and were asked to read and sign the assent or consent form (Refer to Appendix D). Participants were also informed that the data would be de-identified for analysis and that the results would be disseminated as a thesis and a series of scientific journal articles.

Each participant was allocated a number code to de-identify their data, which were entered into an electronic database stored in a firewall-protected local network server managed by Curtin University. The hand-written data were stored in a locked cabinet with restricted access. The electronic data and hard copied data will be kept in these secure conditions for a minimum of 7 years after the completion of the study, and/or until participants have reached 25 years of age. After this time, all data will be destroyed according to the guidelines set by the Western Australian University Sector Disposal Authority.

2.2.3 Experimental design and equipment

The participant particular form, two standardized assessments, and several pieces of equipment were used in the experimental studies. Standardized assessments, such as the Wechsler Abbreviated Scale of Intelligence -

Second Edition (WASI-II) and the Social Responsiveness Scale - Second Edition (SRS-2), were used to profile the characteristics of the participants. In addition, the force platform was used to measure the postural responses of the participants in a virtual reality laboratory.

2.2.3.1 Participant particular form

The participant particular form (Refer to Appendix E) was designed to collect information about the participants, such as name, age, gender, hand dominance, ASD diagnosis, family history of ASD, past medical history, and medication history.

2.2.3.2 Wechsler Abbreviated Scale of Intelligence

Two subtests of the WASI-II Full-Scale IQ were used to attain the verbal and intelligent ability of the participant (Wechsler, 2011). The assessment consisted of the vocabulary and matrix-reasoning components. The vocabulary component comprised a list of words while the matrix-reasoning component contained several puzzles, both of varying difficulties (Wechsler, 2011). A person with an IQ score below 70 is classified as having an intellectual disability.

2.2.3.3 Social Responsiveness Scale

The SRS-2 was used to acquire the severity of ASD symptoms of the participants (Constantino & Todd, 2005). Both the adult self-report and school-age versions consisted of 65 questions pertaining to one’s response in natural and social settings (Constantino & Todd, 2005). It has high sensitivity (85%), high specificity (83%), and acceptable internal consistency (α = 0.71 to 0.89) (Bölte, 2012). A person with an SRS score of 59 and above is classified as having autistic-like social behaviors.

2.2.3.4 Force platform

The AMTI AccuGait portable force platform (Advanced Mechanical Technology Inc., Watertown, MA) was used to measure postural control change in response to visual stimuli and to assess the postural stability of the participants. The force platform measured 50.2 cm in length and width, and 4.5 cm in depth, and had a maximum load capacity of 1334 N. This force platform recorded anteroposterior, mediolateral, and vertical ground reaction forces during quiet standing at a sampling rate of 1000 Hz. In addition, the ground reaction forces were time-stamped to provide a temporal order among the various trials in the postural control assessment.

2.2.3.5 Virtual reality laboratory

The virtual reality laboratory was used to create an immersive environment for the assessment of postural control in ecologically valid environments. The laboratory, located in the Hub for Immersive Visualization and eResearch (HIVE) at Curtin University, consisted of a four-meter half-concave-dome screen and a three-dimensional projection display system. The screen was surrounded by heavy blackout curtains to block out lights from external sources (Figure 2.1).

Figure 2.1 Photo of the concave-dome projector screen.

The Projection Design F35 projector (Projectdesign, Gamle Fredrikstad, Fredrikstad), a three-dimensional projection display system, was used to project various visual stimuli in 180º panorama view. The specifications of the wide quad extended graphics array resolution digital light processing projector included a 2,560 x 1,600 resolution with a refresh rate of 60 Hz, 360-degree rotation lens, and active three-dimensional stereo compatibility.

2.2.3.6 Visual stimuli used in the quiet standing assessments

Visual stimuli were created using the Unity software (Unity Technologies, San Francisco, CA). There were three visual stimuli design.

(1) A red dot with a white border: the visual stimulus design consisted of a red dot positioned in the center of the projector screen, surrounded by a white border (Figure 2.2). The red dot was used as a fixation point for the assessment of postural control.

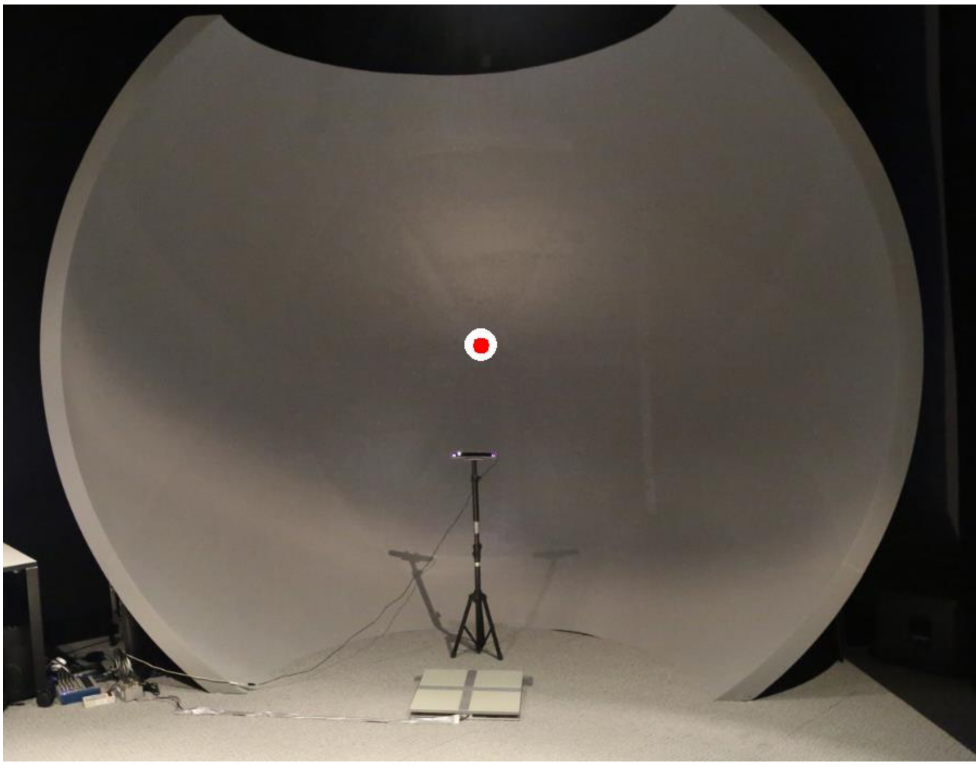

Figure 2.2 Illustration of the red dot with a white border on the screen.

(2) Moving dot pattern: the visual stimulus design consisted of a moving dot pattern and was used as a simulation of the real-world visual environment for the assessment of postural control.

The moving dot pattern was adapted from the studies by Greffou et al. (2008) and Raffi et al. (2014). The visual stimulus used by Greffou et al. (2008) comprised of a virtual tunnel paradigm where a tunnel of 20 m long by 3 m wide was lined throughout with a checkerboard pattern. When the virtual tunnel paradigm oscillated in a front-back motion, it created a three-dimensional virtual reality environment that induced self-motion in observers, causing their posture to be unstable. In contrast, the visual stimulus used by Raffi et al. (2014) comprised a set of two-dimensional dot pattern designs that from a point of origin move radially to the side of the screen. The radial motion of the dots modeled the light pattern movement in the real-world environment (Wade & Jones, 1997). In addition, each dot pattern varied in the flow direction and visual field dimension, enabling the evaluation of how the visual field dimension could affect the control of posture (Raffi et al., 2014).

Drawing on various aspects of the visual stimulus designs from the studies by Greffou et al. (2008) and Raffi et al. (2014), an original moving dot pattern was conceptualized. The six characteristics of the moving dot pattern design used in the experimental studies are described below.

i. The design employed a virtual tunnel paradigm. The tunnel paradigm consisted of a black-colored cylinder-shaped tunnel that was 10 m long and 4 m wide (Figure 2.3). The front of the tunnel expanded across the four-meter diameter projector screen, displaying a viewing angle of 180º. The element of depth from the tunnel paradigm provided the three-dimensional perception observed in the real-world situation (Parsons, 2015).

ii. The design applied shadow shading on the white spherical dots. While two-dimensional dot patterns have been commonly used in the literature (Gepner et al., 1995; Gepner & Mestre, 2002), they can appear flat and do not contribute to the creation of an ecologically valid environment in test settings. In order to reproduce realistic light patterns as observed in the real-world environment, shadow shading was applied to the dots. The shadings on the dots added a degree of depth and realism to the virtual environment, creating a realistic three-dimensional illusion when projected onto the screen (Haller et al., 2003).

iii. The design included dot patterns flowing in two different directions. The dots moved in a randomized radial movement along the tunnel paradigm either towards the observer (the focus of expansion) or away from the observer (the focus of contraction) (Greffou et al., 2012; Greffou et al., 2008; Raffi et al., 2014). These two directions of flow represent the light pattern flow when a person walks forward and backward, respectively. Additionally, when the dots exited the screen at the front or the back of the tunnel, they were automatically recreated so that the projector screen was constantly filled with a stream of continuous moving dots.

iv. The design considered the dot density in the dot pattern. A large enough number of dots were needed to fill the entirety of the projector screen. If the number was too small, the dot pattern will appear sparse and may not create the ideal self-motion illusion (Lestienne et al., 1977). After a few trials during the designing phase, the decision was to use 5000 white-colored spherical dots

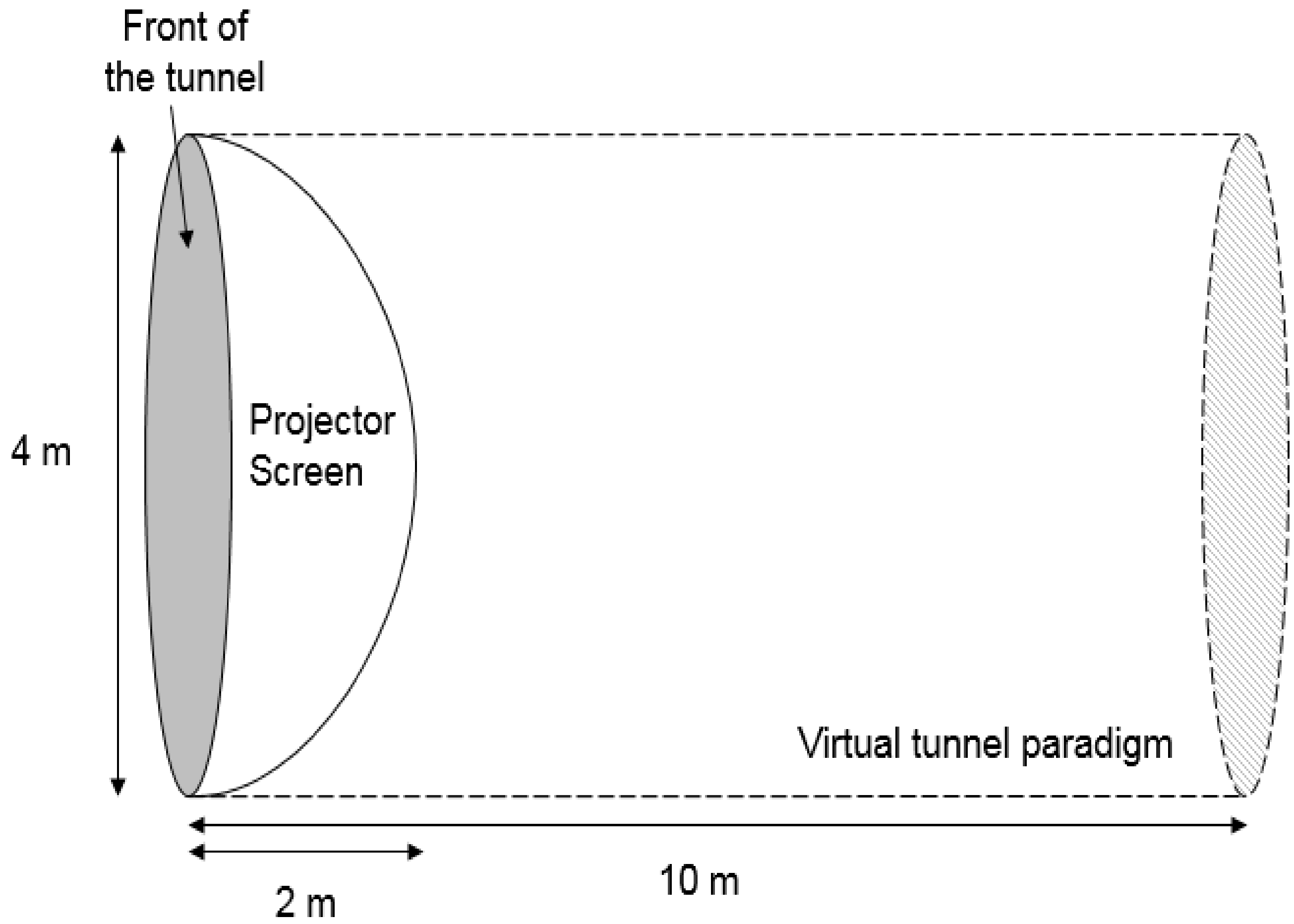

Figure 2.3 Illustration of the tunnel paradigm.

v. The design imitated optic flow properties observed in the natural environment. In the natural environment, the view of a moving object becomes progressively larger as it moved toward the observer (Diaz et al., 2017; Lee, 1980). Therefore, the size of the dot was designed to increase as it moved toward the front of the tunnel. In addition, a fast-enough optic flow speed is required to induce body sway during quiet standing (O'Connor et al., 2008). The author conducted a series of trials during the designing phase to select the optimal speed for the study. Eventually, the speed of 20 m/s was chosen for the moving dot pattern.

vi. The design considered the appearance of the visual field dimensions of the dot pattern. One of the objectives of the thesis was to look at how differing visual field dimensions could affect postural control and thus three visual field dimensions were chosen. The three visual field dimensions focused on the full visual field (FV), central visual field (CV), and peripheral visual field (PV). The FV stimulus contained a dot pattern that spanned across 180º of the projector screen (Figure 2.4A). The CV stimulus contained a dot pattern displayed only within 10º from the center of the screen (Crowell & Banks, 1993; Nougier et al., 1997) (Figure 2.4B). The PV stimulus contained a dot pattern displayed beyond 30º from the center of the screen (Lawrence et al., 2006; Piponnier et al., 2009) (Figure 2.4C). The area between 10º and 30º from the center of the screen was not altered in order to provide a clear distinction between the CV and PV stimulus.

Overall, six moving dot patterns were created for the postural control assessment: (1) FV expansion, (2) FV contraction, (3) CV expansion, (4) CV contraction, (5) PV expansion, and (6) PV contraction. Examples of the visual stimuli design could be view at this weblink: https://www.youtube.com/watch?v=UF-GPG_Fazo.

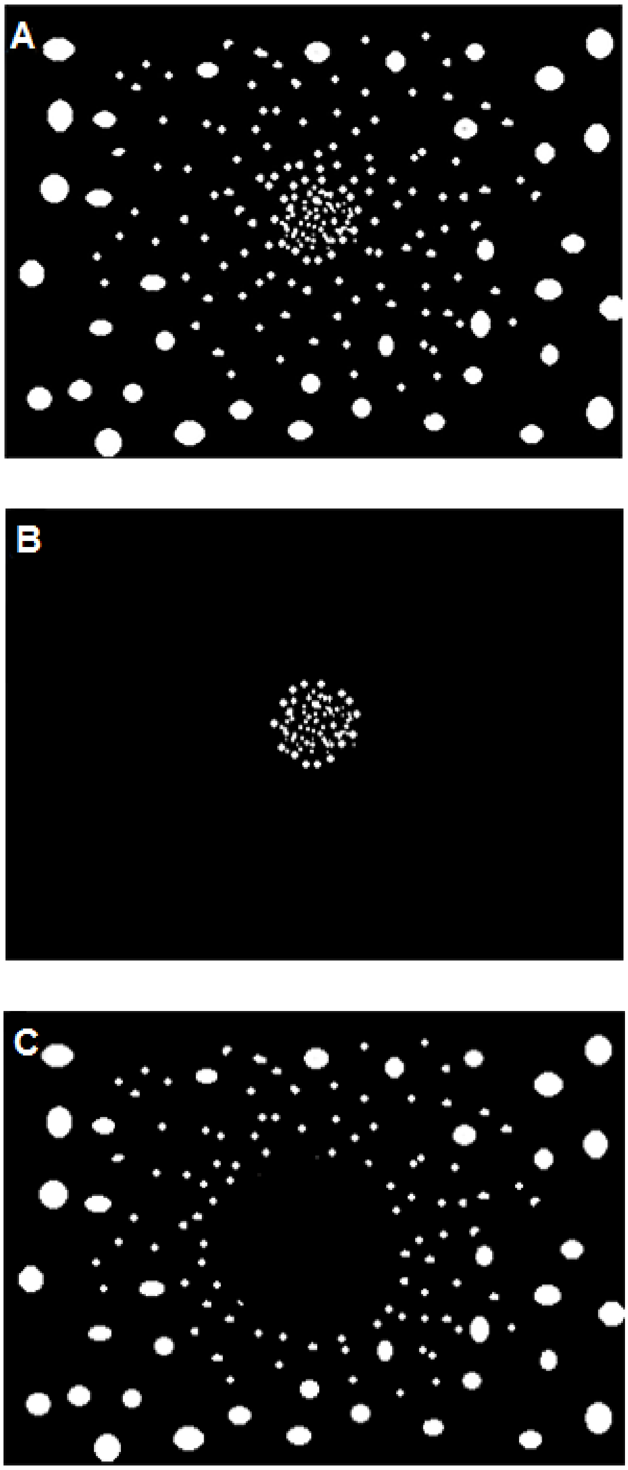

Figure 2.4 Illustration of the different visual field dimensions. (A) The full visual field, (B) the central visual field, and (C) the peripheral visual field.

(3) Static dot pattern: the visual stimulus design was a static dot pattern that consisted of a 1-millisecond snapshot of the moving dot pattern (Figure 2.4A).

The author piloted the final versions of the visual stimuli before they were used in the study. One set of six moving dot patterns and static dot pattern stimuli was shown to the participants during the quiet standing assessments in trial 1 and repeated again in trial 2. The presentation of the visual stimuli was controlled by the SMI Experiment Centre software (SensoMotoric Instruments, Teltow) and followed a pre-randomized order generated by a computerized list randomizer from https://www.sealedenvelop.com (Table 2.1).

Table 2.1 Pre-randomized presentation order of the visual stimulus

Order	Visual stimulus
Trial 1	
1	FV static
2	FV contraction
3	CV contraction
4	CV expansion
5	PV expansion
6	PV contraction
7	FV expansion
Trial 2	
8	FV static
9	CV contraction
10	FV expansion
11	CV expansion
12	FV contraction
13	PV expansion
14	PV contraction

2.2.3.7 Setup of the experimental study

The force platform was set up to be connected to the AMTI amplifier, then to the data acquisition card, analog-to-digital converter (National Instruments, Sydney, NSW), which converted continuous analog waveforms into digital signals of 100 Hz (National Instruments, 2018), and lastly to a computer. The location of the force platform was chosen to be two meters from the middle of the half-dome concave projection screen to allow observers to obtain an entire view of the screen from that specific location.

In addition, a RED250Mobile remote eye tracker (SensoMotoric Instruments, Teltow), with accuracy within 0.4º of the visual field, was connected to the computer. It was used to obtain the gaze position of the participants and operated with a sampling frequency of 60 Hz. The specific functions of the eye tracker that were used included the binocular mode, 9-points calibration test, and time-stamping. The eye tracker was placed on an adjustable floor stand and positioned approximately 60 centimeters in front of the participants when they stood in the middle of the force platform. The floor stand was painted black to reduce its potential use as a visual aid for postural control. The force platform, eye tracker, and visual stimuli were operated using a desktop computer (Asus Tower PC) that ran on Microsoft Windows 7, Intel Core i5 processor, and Nvidia graphics processor. The desktop was also connected to the concave-dome screen. The equipment configuration is shown in Figure 2.5. The body movements recorded on the force platform and eye gaze movements recorded on the eye tracker could be viewed on the desktop computer screen.

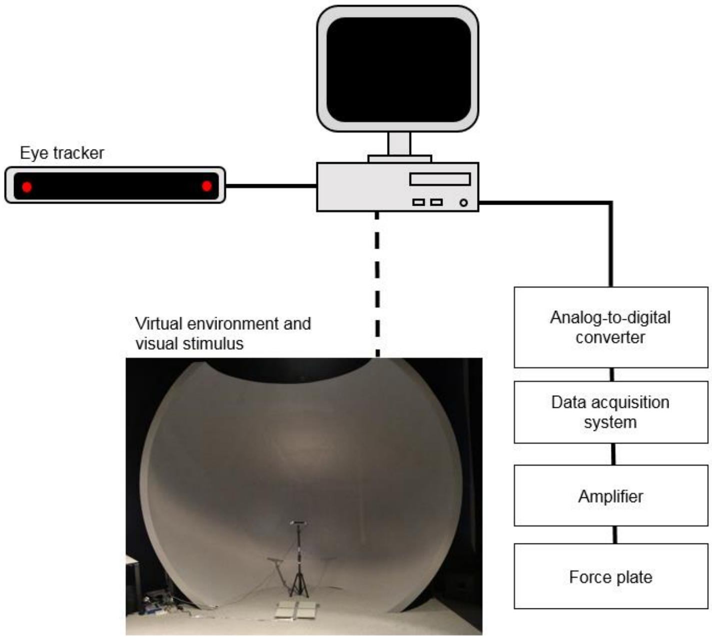

Figure 2.5 Schematic diagram of the equipment configuration for the quiet standing assessments.

2.2.4 Data collection procedure

Participants were required to provide consent or assent before the author administered the participant particular form and WASI-II on the participants. SRS-2 was completed by the participants or caregivers of the child participants, after which, participants underwent a postural control assessment in the virtual reality laboratory. The study took an estimated two to three hours to complete. A token of appreciation was provided at the end of the study to thank the participants for their participation.

The author briefed the participants on the postural control assessment protocol in the virtual reality laboratory. To assess postural stability, participants had to stand with their feet shoulder-width apart while they looked at a static target for 30 seconds, followed by eyes closed for 30 seconds. To assess change in postural control in response to moving stimuli, participants had to stand with their feet together while they looked at the center of the screen for 60 seconds. After that, the author switched off the lights and closed the curtains surrounding the concave-dome screen. Participants had to stand barefooted in the middle of the force platform. Then, they performed an eye-tracking calibration test to verify the accuracy of the eye gaze detection during the study. Thereafter, the procedure differed according to the different objectives of the thesis. Specific details of the different protocols can be found in the methods section of Chapters 4, 5, 6, and 7. Across all protocols, however, participants were reminded to stand as still as possible and to look at the center of the screen throughout the assessment in order to ensure that the change in postural control was in response to the intended design of the visual stimulus.

At the end of every visual stimulus display, participants were asked to step down from the force platform and to rest for approximately 1 minute. The rest break was implemented to minimize the possible development of motion sickness and/or eyestrain. Participants were advised to inform the author if they experienced any symptoms of discomfort. At any point, the assessment could be stopped and they would be attended to. An adverse event management plan (Refer to Appendix F) was created and was to be followed in the case of participant's complaint of discomfort that did not cease with rest.

2.2.5 Outcome measures to assess postural control

The experimental studies used both linear and nonlinear measures of postural control. Linear measures of postural control were used to characterize the stability of postural control (Paillard & Noe, 2015) and were computed with center-of-pressure derived from the ground reaction forces in the anteroposterior (AP) and mediolateral (ML) directions. Center-of-pressure refers to the point where the weighted average of all the pressures over the ground surface contacts with the force platform (Winter, 1995). The five linear measures of postural control were (i) average deviation of the center-of-pressure from the baseline position in the AP plane, AP_{mean}, (ii) average deviation of the center-of-pressure from the baseline position in the ML plane, ML_{mean}, (iii) root mean square (RMS) of the average deviation of the center-of-pressure from the baseline position in the AP plane, *RMS AP,* (iv) RMS of the average deviation of the center-of-pressure from the baseline position in the ML plane, *RMS ML,* and (v) mean velocity.

The average deviation of the center-of-pressure from the baseline position represents the mean center-of-pressure location from the starting center-of-pressure location, expressed by:

$$AP_{mean} = \frac{1}{N}\sum_{n=1}^{N} AP(n)$$

$$ML_{mean} = \frac{1}{N}\sum_{n=1}^{N} ML(n)$$

The RMS of the average deviation of the center-of-pressure from the baseline position represents the standard deviation of center-of-pressure to the mean location, expressed by:

$$RMS\ AP = \sqrt{\frac{\sum_{n=1}^{N}(AP_n - AP_{mean})^2}{N}}$$

$$RMS\ ML = \sqrt{\frac{\sum_{n=1}^{N}(ML_n - ML_{mean})^2}{N}}$$

The mean velocity of center-of-pressure represents the average speed that center-of-pressure travels and is defined as the total excursion distance in the time series divided by the total time duration, expressed by:

$$Mean\ velocity = \frac{\sum_{n=1}^{N-1}(\sqrt{(AP(n+1) - AP(n))^2 + (ML(n+1) - ML(n))^2}}{time}$$

In contrast, nonlinear measures of postural control were used to quantify similar patterns within a postural control time series data (Busa & van Emmerik, 2016; Richman & Moorman, 2000). They included sample entropy in the AP plane and sample entropy in the ML plane. The sample entropy represents the regularity of the AP and ML ground reaction forces in a time series and the attentional demands invested in postural control. It is defined as the negative natural logarithm of the conditional probability that a complete dataset, when divided into shorter dataset length of *m*, would have matches that are within the tolerance range *r* without allowing self-matches (Yentes, 2016). The predetermined value of *m* is 2 and *r* is 0.2. The sample entropy calculation is expressed by:

$$Sample\ entropy\ AP = -log\frac{A}{B}$$

$$Sample\ entropy\ ML = -log\frac{A}{B}$$

where B represents the total number of matches with the dataset length *m* while A represents the total number of matches with the dataset length *m* + 1 (Roerdink et al., 2011).

Both linear and nonlinear measures of postural control were calculated using MATLAB 2015b (The MathWorks Inc., Natick, MA, USA).

2.2.6 Data processing and statistical analysis

A 5th order Butterworth low pass filter with a cut-off frequency of 10 Hz was applied to the ground reaction forces using MATLAB 2015b (The MathWorks Inc., Natick, MA, USA) to filter noise collected during data collection with the force platform. Subsequently, the processed ground reaction forces were synchronized with the gaze fixation percentage. The gaze fixation percentage was derived from the eye-tracking data and indicated the proportion of the trial that the fixated gaze was detected in the predefined region that was 10º from the center of the screen (Amso et al., 2014). It is expressed by:

$$Gaze\ fixation\ percentage = 100(\frac{N_{hit}}{N_{total}})$$

where N_{total} is the total number of gaze fixation in a trial and N_{hit} is the total number of gaze fixation within the predefined fixation region.

Data from the postural control measurements had to fulfill two criteria to be included for statistical analysis. The first criterion was that data used to calculate the postural control measurement had to be complete. Postural control data recorded from participants who lost their balance during the trial or asked for their trials to be stopped were thus excluded. The second criterion was that every individual data set needed to achieve at least a 90% gaze fixation percentage. These predetermined criteria were necessary to ensure an accurate statistical analysis. Overall, 83% of the data sets met both of the criteria.

A two-steps approach was taken in the statistical analysis of the data using the SPSS ® (Statistical Package for Social Sciences) Version 24 for Windows. The two steps included performing descriptive statistics then inferential statistics.

Descriptive statistics were used to describe and summarize the data set. Data with normal distribution were further analyzed with parametric statistical tests while those that were not normally distributed were analyzed with non-parametric statistical tests.

Inferential statistics consisted of both parametric and non-parametric tests. The parametric test included an independent sample t-test while the non-parametric tests included Fisher's exact test and Mann-Whitney U test. In addition, the linear mixed model by means of backward elimination was chosen to examine between-group differences in the postural control measurements. The linear mixed model was chosen because it can tolerate non-compliance of normality and homogeneity of variance (Harrison et al., 2018). A p-value ≤ 0.05 was considered significant for all analyses but a more stringent p-value ≤ 0.01 was used for post hoc pairwise comparisons of between-group and within-group differences using least-squares means of fixed effects and least square mean difference of fixed effects. Details regarding the statistical tests used in the individual study are reported in the methods section of Chapters 4, 5, 6, and 7.

2.3 Summary

The research methods of the studies employed in the thesis are summarized in Table 2.2.

Table 2.2 Summary of the research methods used in each chapter

Aspect	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Design	Systematic review	Experimental study	Experimental study	Experimental study	Experimental study
Sample	19 empirical studies	14 adults with ASD and 17 TD adults	15 children with ASD and 18 TD children	15 children with ASD, 18 TD children, 15 adults with ASD, and 18 TD adults	15 children with ASD, 18 TD children, 15 adults with ASD, and 18 TD adults
Experiment stimulus	-	A red dot with a white border	A red dot with a white border	Various moving dot patterns	Various moving dot patterns
Statistical analysis	Meta-analysis	Fisher's exact test, Mann-Whitney U test, independent sample t-test, and linear mixed model	Fisher's exact test, independent sample t-test, and linear mixed model	Fisher's exact test, Mann-Whitney U test, independent sample t-test, and linear mixed model	Fisher's exact test, Mann-Whitney U test, independent sample t-test, and linear mixed model

ASD: autism spectrum disorder; TD: typically developed/developing

2.4 References

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Chapter 3 Standing postural control in individuals with autism spectrum disorder: Systematic review and meta-analysis

3.1 Preface

Chapter 3 presents a systematic review of the literature on postural control in individuals with autism spectrum disorder (ASD). Synthesized evidence of postural control in individuals with ASD is necessary because there is a limited understanding of this research area in the current literature. Therefore, this systematic review was conducted to summarize and integrate research evidence in relation to the effect of sensory information on postural control in individuals with ASD and typically developing/developed (TD) individuals. This review identifies the characteristics of postural control in individuals with ASD relative to TD individuals. It is important to note that the term “neurotypical individuals” used in this chapter has the same meaning as the term “typically developing/developed individuals” used throughout the thesis.

This study has been published as “Lim, Y.H., Partridge, K. Girdler, S., & Morris, S.L. (2017). Standing postural control in individuals with autism spectrum disorder: Systematic review and meta-analysis. *Journal of Autism and Developmental Disorders, 47*(7), 2238-2253”. The statement of the primary contribution of the first author can be found in Appendix A.

The final publication is available at Springer via https://doi.org/10.1007/s10803-017-3144y.

Chapter 4 Effect of visual information on postural control in adults with autism spectrum disorder

4.1 Preface

Chapter 4 presents the first of the four studies exploring the influence of visual information on postural control in individuals with autism spectrum disorder (ASD). Postural control studies involving adults with ASD are important because there is currently little understanding of postural control in adults with ASD. Therefore, an experimental study was conducted to investigate the effect of static visual information on postural control in adults with ASD and typically developed adults. The chapter reports on the differences in postural control observed in adults with ASD when compared with typically developed (TD) adults.

This study has been published as "Lim, Y. H., Partridge, K., Girdler, S., & Morris, S. L (2019). The effect of visual information on postural control in adults with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 49*(12), 4731-4739*".* The statement of the primary contribution of the first author can be found in Appendix A.

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The final publication is available at Springer via https://doi.org/10.1007/s10803-018-3634-6.

Chapter 5 Effect of visual information on postural control in children with autism spectrum disorder

5.1 Preface

Chapter 5 presents the second of the four studies exploring the influence of visual information on postural control in individuals with autism spectrum disorder (ASD). This chapter is an extension of the experimental study in Chapter 4. It was not clear if differences in postural control found between adults with ASD and typically developed (TD) adults are also found between children with ASD and TD children. Therefore, this chapter replicates the research methodology in Chapter 4 to investigate the effect of static visual information on postural control in children with ASD and TD children. The chapter reports on the postural control of children with ASD and discusses the postural control development progression in individuals with ASD.

This study has been published as "Lim, Y. H., Partridge, K., Girdler, S., & Morris, S. L (2018). The effect of visual information on postural control in children with autism spectrum disorder. *Journal of Autism and Developmental Disorders".* The statement of the primary contribution of the first author can be found in Appendix A.

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Chapter 6 Effect of optic flow on postural control in children and adults with autism spectrum disorder

6.1 Preface

Chapter 6 presents the third of the four studies exploring the influence of visual information on postural control in individuals with autism spectrum disorder (ASD). Postural control studies with real-world applicability are important to understand how children and adults with ASD respond to visual information in their natural environment. However, few studies have investigated postural control in children and adults with ASD using ecologically valid visual stimuli. In addition, there is little understanding of how the field of vision may affect postural control in children and adults with ASD. Therefore, an experimental study was conducted to investigate the effect of optic flow on postural control in children and adults with ASD and typically developing/developed (TD) controls under ecologically valid visual environments. The chapter reports on the postural responses of children and adults with ASD when responding to a range of optic flow conditions in varying fields of view.

This study has been published as "Lim, Y. H., Lee, H. Falkmer, T., Allison, G., Tan, T., Lee, W. H., & Morris, S. L. (2018). Effect of optic flow on postural control in children and adults with autism spectrum disorder. *Neuroscience, 393,* 138-149*".* The statement of the primary contribution of the first author can be found in Appendix A.

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The final publication is available at Elsevier via *https://doi.org/10.1016/j.neuroscience.2018.09.047*.

Chapter 7 Postural control adaptation to optic flow in children and adults with autism spectrum disorder

7.1 Preface

Chapter 7 is the last of the four-part study series exploring the influence of visual information on postural control in individuals with autism spectrum disorder (ASD). This chapter is a secondary analysis of the study in Chapter 6. It was not clear how children and adults with ASD adjust their posture across different time points when responding to a range of optic flow conditions of varying fields of view. Therefore, this chapter examines the temporal domains of postural control in children and adults with ASD and typically developing/developed controls in response to varying optic flow conditions of varying fields of view. The chapter reports on the differences in time taken to restore postural stability across different age groups.

This study has been published as “Lim, Y. H., Lee, H. Falkmer, T., Allison, G., Tan, T., Lee, W. H., & Morris, S. L. (2019). Postural control adaptation to optic flow in children and adults with autism spectrum disorder. *Gait & Posture, 72*, 175-181”. The statement of the primary contribution of the first author can be found in Appendix A.

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The final publication is available at Elsevier via https://doi.org/10.1016/j.gaitpost.2019.06.007.

Chapter 8 Discussion

8.1 Main findings

People with autism spectrum disorder (ASD) often experience problems with postural control. Despite growing research about postural control in those with ASD, the perspective of postural control in adults with ASD is limited and the understanding of their postural control system in dynamic visual environments remains unclear. To address these gaps in research, the present thesis was conducted using a range of research methodologies and provides a substantial, original, and significant contribution to the understanding of postural control in ASD.

This thesis consists of five studies, including a systematic review and four experimental studies. The systematic review summarized the existing literature relating to postural control in individuals with ASD under a range of sensory conditions and identified the impact of different types of sensory information on postural control in both children and adults with ASD. Following the systematic review are two experimental studies that examined the effect of static visual information on postural control in adults and children with ASD. Next, an experimental study was conducted to examine the effect of immersive optic flow on postural control in children and adults with ASD and to examine how the field of vision impacts on postural control in the ASD cohort. Lastly, a secondary analysis of the experimental study involving immersive optic flow was conducted to understand how children and adults with ASD adjust their posture across different time points during the experiment. The findings are discussed at length in Chapters 3 to 7 and summarized in this chapter. The thesis concludes with the discussion of the strengths and limitations of the present thesis, and recommendations for future research.

8.1.1 Characteristics of postural control in individuals with autism spectrum disorder

The existing research literature strongly supports the evidence of postural control impairments in individuals with ASD. Using 19 studies spanning 434 individuals with ASD and 551 typically developing/developed (TD) individuals, the first study conducted a meta-analysis that computed large effect sizes when comparing various postural control outcomes between the two groups in varying somatosensory and visual conditions (Lim et al., 2017). The meta-analysis indicated that postural control was more unstable in those with ASD when compared with TD controls. This finding is consistent with previous narrative reviews on postural control in individuals with ASD (Downey & Rapport, 2012; Memari et al., 2014), suggesting that postural control is impaired in those with ASD. One other characteristic of postural control in the ASD cohort noted in the first study is the predominant mediolateral movement during quiet standing, which is unlike the predominant anteroposterior movement found in the TD cohort (Lim et al., 2017). The discovery of this unusual characteristic of postural control in ASD substantiates the findings by Kohen-Raz et al. (1992). The mechanism of this difference is unknown, but the mediolateral movement during quiet standing is proposed to be generally dependent on visual information (Warren et al., 1996). Therefore, the predominant mediolateral movement in the ASD cohort suggests that, between the somatosensory and visual systems that provide information for postural control, the visual system in those with ASD seemed to be different from that of the TD cohort (Lim et al., 2017).

In addition, postural control impairments in children with ASD did not appear to improve with age. The first study found that differences in postural control outcomes were detected in studies involving both children and adults with ASD; although, only 6 out of 19 (31.6%) studies in the systematic review involved adults with ASD (Lim et al., 2017). This finding supports prior studies that have reported anecdotal and clinical accounts of movement disturbances in both children and adults with ASD (Donnellan et al., 2012; Leary & Hill, 1996; Minshew et al., 2004), suggesting that postural control impairments are present in both children and adults with ASD. This finding is important because postural control in adults with ASD is not well-understood due to the under-represented empirical evidence of postural control in adults with ASD in the current literature. Poor postural control in adults with ASD is of concern to those who desire to work and live independently. Unlike in a supported home and school environment, adults with ASD would be expected to engage in more difficult motor tasks in workplaces and in the community with limited help (Happe & Charlton, 2012; Thompson et al., 2018), such as heavy lifting and overhead reaching while maintaining a stable posture. At present, it is not clear whether the difficulties that adults with ASD face in their daily tasks are associated with postural control impairments. Furthermore, there is a limited understanding of the impact of declining physical functioning and postural control impairments in older adults with ASD. Further exploratory studies on postural control in adults and older adults with ASD would be necessary to bridge the research gaps in the literature.

8.1.2 Influence of visual information on postural control in individuals with autism spectrum disorder

Certain features in the visual environment seem to increase the postural responses of adults with ASD when compared with TD adults. The experimental studies found that postural responses were different between adults with ASD and TD adults only when they underwent quiet standing while looking at a central fixation point and while looking at a forward-moving optic flow shown in the peripheral visual field (Lim et al., 2018a, 2018b). In contrast, postural control was similar between children with ASD and TD children in all visual conditions (Lim et al., 2019a), suggesting that increased responsiveness to sensory stimuli might be more observable in adults with ASD than in children with ASD. The difference in postural response between the ASD and TD adult groups when looking at a forward-moving optic flow shown in the peripheral visual field is an original finding that has not been reported in prior ASD literature. It is important to understand that in this visual environment, participants had to fixate on a black static central circle while light patterns flowed forward in their peripheral visual field (Lim et al., 2018a). As a result, this created a busy, incoherent, and unfamiliar visual environment for the participants (Edwards & Ibbotson, 2007; Holten et al., 2015). Individuals with ASD have previously been found to be affected by busy and incoherent visual information, displaying signs of sensory over-responsiveness and errors in performance, respectively (Green et al., 2016; Robertson et al., 2014). This finding also suggests that adults with ASD could have a reduced capacity to attend to the central visual field and to ignore the peripheral visual field. Thus, these findings suggest that visual environments that are busy, incoherent and unfamiliar could potentially increase the sensory responsiveness in individuals with ASD, which could affect their postural control. While this is an important finding that extends the understanding of the influence of visual information on postural control in the ASD cohort, further research is needed to confirm this original finding.

The amount of attention invested in postural control in individuals with ASD appears to be dependent on the use of visual information. The present thesis found that adults with ASD tended to invest a larger amount of attention on their mediolateral movement than TD adults when standing with their eyes open (Lim et al., 2018b). Although a statistically significant difference was not observed between school-age children with ASD and TD school-age children, school-age children with ASD also appeared to invest a larger amount of attention on mediolateral movement during standing than TD school-age children (Lim et al., 2019a). This finding is consistent with one other study that measured the amount of entropy, related to attentional measures, in ASD and TD preschool children during quiet standing (Fournier et al., 2014). This finding is important as it shows that attending to visual information while standing has the capacity to reduce the available attentional resource in individuals with ASD. Each individual only has a limited amount of attention (Remaud et al., 2012), and thus the larger amount of attention invested by adults with ASD during standing while attending to a visual task suggests that visual processing problems could contribute to postural control problems in adults with ASD.

The speed of restoration of postural control in response to changes in visual information depends on age. The experimental studies found that individuals with ASD and TD individuals were able to restore their posture despite initial posture perturbation when there were changes in their visual environments (Lim et al., 2019b). However, children with ASD and TD children took an average of 20 seconds longer to do so than adults with ASD and TD adults. This is an original finding that has not been reported in the prior research literature. This finding suggests that information processing speed within the human postural control system tends to improve with age (Polastri & Barela, 2013; Rinaldi et al., 2009) and that children and adults with ASD are not different from their TD controls in terms of information processing for postural control. The finding of no between-group difference in response time to restore posture is important as it could eliminate the concern of time delay as a contributor to postural control impairments in the ASD cohort (Franklin & Wolpert, 2011). Nonetheless, there is scope for more investigation to ascertain this original finding.

8.1.3 Postural control system in individuals with autism spectrum disorder

The postural control system in individuals with ASD could be understood through the optimal feedback control framework (Figure 1.5, “Diagram of the optimal feedback control framework of the sensorimotor control system”) proposed by Todorov (2004). The findings in the present thesis when analyzed using the framework revealed that certain components of the postural control system in individuals with ASD appeared to be different from that of TD individuals. The description of the postural control system in individuals with ASD using this approach has not been reported before in previous literature. The section below provides an overview of the four components within the postural control system of those with ASD.

The first component is the state of the person’s body in relation to the environment that commences the process of the postural control system (Todorov, 2004). In the present thesis, children with ASD and TD children, and adults with ASD and TD adults were comparable in height and weight, as well as being in similar quiet standing positions (Lim et al., 2018a, 2018b; Lim et al., 2019a). It is likely that the body state of all participants is alike; although, some studies have reported the presence of low muscle tone in children with ASD that could alter their body state (Serdarevic et al., 2017). Therefore, it is not possible to suggest if postural control impairments in ASD are influenced by differences in the person's body state in the present thesis.

The second component is the sensory systems that collect pertinent information to inform the state of the person's body (Todorov, 2004). In the present thesis, postural control between adults with ASD and TD adults in response to a static central target with and without unfamiliar moving light patterns flowing in the peripheral visual field were different (Lim et al., 2018a, 2018b). These findings suggest that postural control in adults with ASD is challenged by certain sensory stimuli collected during the reception and processing of visual information. Evidence of heightened responsiveness to sensory stimuli in individuals with ASD, especially visual stimuli, has been reported in previous studies (Dinstein et al., 2010; Goh et al., 2018; Simmons et al., 2009; Zaidel et al., 2015). Heightened responsiveness to visual stimuli could be due to altered network connectivity within the visual system (Ward, 2019), which is consistent with the discussion in Chapter 1.5, "Autism spectrum disorder and postural control" regarding atypical magnocellular pathways in individuals with ASD (Bakroon & Lakshminarayanan, 2016; Burt et al., 2017; Crewther et al., 2015; Spencer et al., 2000). It could be plausible that altered network connectivity results in increased sensory noise within the visual system (Ward, 2019), and thus affect the feeding of accurate sensory information into the postural control system (Faisal et al., 2008). Therefore, it may be possible to suggest that postural control impairments in ASD could be influenced by altered network connectivity from somewhere in the visual system.

The third component is the state estimator that integrates sensory information from the sensory systems to form an estimate of the person's body (Todorov, 2004). With postural responses of adults with ASD found to be different from TD adults in certain visual environments (Lim et al., 2018a, 2018b), this could suggest that, despite being in the same quiet standing position, adults with ASD might be processing and integrating visual information differently from TD individuals. Problems with sensory and motor information integration could lead to the construction of a faulty internal representation of the state of their body in relation to the environment (Peterka, 2002). Several studies have proposed that problem with integration in ASD could be due to hyper-connectivity in the brain (Markram & Markram, 2010; Ward, 2019) because of strong evidence of unusually dense connectivity of sensorimotor and visual networks in individuals with ASD (Chen et al., 2018; Shen et al., 2016). Therefore, there is a possibility that postural control impairments in ASD are influenced by atypical sensorimotor network connectivity.

The fourth component is the optimal feedback controller that produces motor commands based on the estimated state of the person's body (Todorov, 2004). In the present thesis, children with ASD and TD children, and adults with ASD and TD adults did not differ in terms of time taken to restore postural stability in response to optic flow (Lim et al., 2019b). In these circumstances, sensorimotor information transmission in children and adults with ASD might not have been delayed relative to their TD controls. Therefore, there is a possibility that postural control impairments in ASD are not explained by sensorimotor delays.

Overall, findings from the present thesis show that the postural control system in individuals with ASD is different from TD individuals. This difference may occur in the sensory systems and/or the sensorimotor integration components, suggesting that mechanisms underlying postural control impairments in ASD might be found in the early visual system and brain regions responsible for sensory integration. While the framework has been useful in identifying problem areas within the postural control system of individuals with ASD, a challenge with the framework-based interpretation is the translation of its findings into a practical interpretation of the neural circuits in the brain. Additionally, the framework did not take into account some other factors that could affect the postural control system, for example, cognitive resources, such as attention (Horak, 2006). Given that the present thesis has found a larger investment of attention on postural control in adults with ASD when they look at visual information, further understanding of how attention could affect the transmission of sensory information within the postural control system would provide better insight into the mechanism underlying postural control impairments in ASD. Nonetheless, the use of the optimal feedback control framework of the sensorimotor system has contributed a structured approach to identify problem areas in the postural control system of individuals with ASD.

8.2 Strengths and limitations of the thesis

The present thesis appears to be among the few studies that investigated postural control in both children and adults with ASD. The use of both child and adult participants is important as it has uncovered new knowledge of postural control in ASD, especially from the perspective of adults that is limited in the existing literature. However, the thesis could have benefited from tightening the age range of the adult participants to be within a range of 20 years. In the thesis, the age range of the adult participants was 32 years, with participants' age ranging between 18 and 50 years old. Even though the participants in the upper limit age range were healthy and had no physical anomalies, there could be a confounding factor of age on postural control assessment because age-related changes of the postural control system have been associated with older adults (Baloh et al., 1994; Paillard, 2017). Nevertheless, since 31 out of 33 (94%) adult participants were within the age range of 18 and 38, the risk of age as a significant confounding factor in the thesis is limited. In addition, the thesis could have benefited from the exploration of postural control in individuals with different levels of ASD severity to understand the influence of the levels of severity on postural control impairment in ASD.

A critical aspect of the thesis is the use of virtual reality technology to create immersive visual environments for the assessment of quiet standing. While this approach has been commonly employed in studies involving TD and various neurological disorder cohorts (Cano Porras et al., 2018; Greffou et al., 2008; Lubetzky et al., 2018; Raffi et al., 2014), it has rarely been used in ASD studies. The use of visual environments with relevance to the real world is necessary because research involving basic and static stimuli may not provide many crucial aspects of real-world interactions and may not be useful in translational research (Parsons, 2015). Furthermore, the benefits of using virtual reality technology included the ability to tailor the visual environments to meet the aims of the thesis, for example, changing the flow direction of the light patterns and the visual field dimension size. However, the present thesis could have benefited from having moving dot patterns of various speeds. Understanding how one's posture is influenced by the speed of object movement in the environment would provide insights into another aspect of postural control as observed in the real world. Nonetheless, the manipulation of the flow direction of light patterns and the visual field dimension size in the present thesis through the use of virtual reality technology is a novel approach in the ASD literature and the research findings have real-world applicability for used in translational research in the future.

The sample size in the thesis can be considered sufficient. Despite two to three hours required from each participant in the experimental studies, a total of 66 participants have completed the study. However, the present thesis could have benefited from having more participants. In the experimental studies, each group had approximately 14 to 18 participants. Based on the mean postural responses collected from the optic flow in contraction peripheral visual field condition, these sample sizes yielded an average F-test effect of 0.40 and a statistical power of 0.68 based on repeated measures analysis of variance with a 5% critical alpha level. As the statistical power is slightly under the recommended value of 0.80, there could be a risk of a type II error when interpreting the results. Nevertheless, the sample size in the present thesis is comparable to other postural control studies in the ASD literature (Chen & Tsai, 2015; Doumas et al., 2016; Morris et al., 2015) and could be considered an acceptable compromise because a statistically significant difference between groups could be detected in the analysis of data from the current sample size (Lim et al., 2018a, 2018b).

The present thesis is among the few studies in the ASD literature to use an eye-tracking device to monitor the eyes gaze of the participants during the quiet standing assessment. The collection of eye-tracking data has enabled the author to filter the postural control data in accordance with the experimental study protocol, which is to include only data of participants who adhered to the task of fixating on the center of the screen throughout the assessment of quiet standing into data analysis. However, filtering the data could pose a risk of removing a large amount of data from the ASD group as individuals with ASD have been reported to look more in their peripheral visual field instead of their central visual field when looking at photos consisting of people's faces (Joseph & Tanaka, 2003; Rutherford et al., 2007). A post-hoc analysis of the eye-tracking data was done and it showed that individuals with ASD adhered to the task of fixating on the center of the screen as well as TD individuals, with the exception in two visual conditions: forward-flowing optic flow concentrated in the central visual field and backward-flowing optic flow shown across the full visual field (Appendix G). Although a larger number of children with ASD appeared to look away from the center of the screen during these two conditions than TD children, group difference in postural responses between the children groups were not expected as the present thesis did not find group difference in postural responses between the adults groups in these visual conditions (Lim et al., 2018a). Therefore, the risk of a type I error is minimal.

8.3 Recommendations for future research direction

While the findings in the present thesis have made a substantial, original, and significant contribution to the understanding of postural control in ASD, there is still potential for future investigation to advance the knowledge in this field of study. Further research is necessary to ascertain the many original findings reported in this thesis. The thesis, being of an exploratory and interpretive nature, raises many new directions for future research.

There is scope for research to further understand the impact of visual attention on postural control in individuals with ASD. Visual attention is known to influence postural control (Horak, 2006; Stins et al., 2015) and has the ability to improve the transmission of sensory information that can potentially reduce sensory noise in the visual system (Briggs et al., 2013). However, it is not known if a combination of increased sensory noise in the visual system (Cusack et al., 2015; Zaidel et al., 2015) alongside atypical attention processing (Ames & Fletcher-Watson, 2010; Smith & Schenk, 2012) contribute to postural control impairments observed in those with ASD. An understanding of how visual attention adjusts sensory noise in the visual system and subsequently postural control is important to reveal further insights into the postural control system in individuals with ASD and to guide the development of interventions for postural control.

Moreover, future research may consider a longitudinal approach to study postural control development in children with ASD. Postural control in children is known to improve with age and prior cross-sectional studies involving TD children have provided important knowledge about the development of postural control in children (Sá et al., 2018; Steindl et al., 2006; Verbecque et al., 2016). However, little is known about the development of postural control in children with ASD. Child participants across existing studies in the ASD literature have been largely confined to school-aged children (Chen & Tsai, 2015; Fournier et al., 2010; Lim et al., 2019a; Price et al., 2012). A cross-sectional understanding of postural control in children with ASD across different age groups, such as infants, preschool-aged children, school-aged children, and adolescents, is important and would provide invaluable information about the developmental progression of postural control in the ASD cohort. Understanding postural control development in ASD could contribute to the development of early differential diagnostic tools and interventions for those with ASD.

In addition, it may be beneficial to study postural control in older adults with ASD. Older adults tend to be susceptible to falls possibly due to age-related changes in the postural control system (Horak, 2006; Tinetti & Kumar, 2010). However, it is not known if and how pre-existing postural control impairments combined with age-related changes in the postural control system would increase the risk of falls in older adults with ASD. Future postural control investigations involving older adults with ASD would contribute to the development of falls risk assessment and falls prevention efforts at home and in the community.

Researchers may be interested to understand the differences in postural control of individuals with ASD and individuals with other neurodevelopmental disorders. While there is evidence of postural control impairments in individuals with ASD (Lim et al., 2017), developmental coordination disorder (Wilson et al., 2013), and attention-deficit/ hyperactivity disorder (Kaiser et al., 2015), the understanding of how postural control of each cohort compared with each other is limited. The comparison of postural control in different cohorts could provide unique and novel information relating to the postural control profile of each cohort. The findings from future postural control investigations involving different neurodevelopmental disorder cohorts might reveal knowledge relevant for diagnosis and intervention.

It may be also worthwhile to examine postural control in conjunction with physiological monitoring methods to identify neural mechanisms underlying postural control impairments in individuals with ASD. Physiological monitoring approaches, such as functional near-infrared spectroscopy and functional magnetic resonance imaging, are increasingly used to identify regions of the brain responsible for postural control impairments in pathology conditions (Mihara et al., 2012; Zwicker et al., 2011). Findings from studies using these approaches could be crucial to examine sensorimotor network connectivity during postural control in the light of heightened responsiveness to visual stimuli in individuals with ASD.

8.4 Conclusion

This present thesis is among the few studies to investigate postural control in both children and adults with ASD. Postural control impairments in ASD could be associated with increased visual noise and sensorimotor integration deficits related to altered network connectivity. Further investigations to understand the mechanism underlying visual noise and sensorimotor integration deficits within the system is warranted.

Overall, David will still experience postural control problems as a feature of ASD. However, there is hope that the growing research in postural control in ASD will enhance the understanding of postural control in this cohort and subsequently guide the development of interventions for postural control so that David can safely do what he loves – running.

8.5 References

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- Data collection, analysis, and interpretation;
- Writing the manuscript and critical appraisal of the findings;
- Corresponding author responsible for communication with the journal

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Chapter Seven

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Rights and Access

Postural control adaptation to optic flow in children and adults with autism spectrum disorder

Corresponding author	Miss Yi Huey Lim
E-mail address	yihuey.lim@postgrad.curtin.edu.au
Journal	Gait & Posture
Our reference	GAIPOS6825
PII	S0966-6362(18)31922-2
DOI	10.1016/j.gaitpost.2019.06.007

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Appendix C Human research ethics approval letter

MEMORANDUM

Curtin University

To:	Dr Hoe Lee School of Occupational Therapy and Social Work
CC:	
From	Professor Peter O'Leary, Chair HREC
Subject	Ethics approval Approval number: HR28/2016
Date	29-Feb-16

Office of Research and Development
Human Research Ethics Office

TELEPHONE 9266 2784
FACSIMILE 9266 3793
EMAIL hrec@curtin.edu.au

Thank you for your application submitted to the Human Research Ethics Office for the project: 6528

The contribution of central and peripheral vision on postural control during standing in adults with Autism Spectrum Disorders

Your application was reviewed by Human Research Ethics Committee at Curtin University at their meeting on the 02/02/2016

Thankyou for providing the additional information requested by the Human Research Ethics Committee. The information you provided was satisfactory and your proposal is now approved.

Please note the following conditions of approval:

1. Approval is granted for a period of four years fror **01-Mar-16** to **01-Mar-20**
2. Research must be conducted as stated in the approved protocol.
3. Any amendments to the approved protocol must be approved by the Ethics Office.
4. An annual progress report must be submitted to the Ethics Office annually, on the anniversary of approval.
5. All adverse events must be reported to the Ethics Office.
6. A completion report must be submitted to the Ethics Office on completion of the project.
7. Data must be stored in accordance with WAUSDA and Curtin University policy.
8. The Ethics Office may conduct a randomly identified audit of a proportion of research projects approved by the HREC.

Should you have any queries about the consideration of your project please contact the Ethics Support Officer for your faculty, or the Ethics Office at hrec@curtin.edu.au or on 9266 2784. All human research ethics forms and guidelines are available on the ethics website.

Yours sincerely,

Professor Peter O'Leary
Chair, Human Research Ethics Committee

Appendix D Participant information statements and consent forms

Curtin University

ASD visual field

PARTICIPANT INFORMATION STATEMENT

HREC Project Number:	HR 28/2016
Project Title:	*The contribution of central and peripheral vision on postural control during standing in adults with Autism Spectrum Disorders*
Principal Investigator:	*Dr Hoe Lee, Associate Professor*
Student researcher:	*Yi Huey Lim*
Version Number:	*4*
Version Date:	*15/06/2017*

What is the Project About?

Having good balance is important for movement. Our ability to balance depends on the information from our ears, eyes, and touch. Eyesight has an important role in balance because we need to see in order to interact with our environment. However, there is insufficient knowledge in understanding how vision influences the way people stand or move. We want to understand how people with and without Autism Spectrum Disorders (ASD) respond to changes in their visual environment, and how vision influences balance.

This study aims to investigate the impact of vision on balance in adults with ASD. The study will require participants with ASD.

Who is doing the Research?

The project is being conducted by Yi Huey Lim and this research will contribute to a higher educational qualification of this student researcher. The results of this research project will be used by Yi Huey Lim to obtain a Doctorate of Philosophy at Curtin University.

Why am I being asked to take part and what will I have to do?
You have been asked to take part in this study because you have identified yourself as:

- Between 18 – 50 years old
- Have been clinically diagnosed with ASD or Asperger Syndrome
- Able to provide written consent in English
- Can see afar without wearing spectacles
- Willing to stand for 30 minutes (with interval rest breaks)
- Have no history of seizure

If you agree to participate in this study, you will be required to complete the social responsiveness scale test, visual acuity, IQ, sensory profile, and motor skill assessments. You will be required to stand still on a force platform in bare feet, in the dark and watch a screen with moving dots. In addition, you will be required to wear a cap that will measure your brain activity during the study. The study will take approximately 3 hours to complete. The study will be conducted in Curtin University. There will be no cost to you for taking part in this research and you will be reimbursed for your inconvenience with a $20 Coles/Myer gift card upon completion of the study.

We would like you to consider allowing us to send you information about future research projects. Once you receive the information it is your choice if you decide to take part or not.

Are there any benefits to being in the research project?
There may be no direct benefit to you for participating in this research. However, your participation in this study may benefit people with ASD in the future. We hope the results of this research will allow us to:

- Optimise early intervention programs
- add to the knowledge we have about this condition

Are there any risks, side effects, discomforts or inconveniences from being in the research project?
The possible discomfort in this study may include feeling uncomfortable being in a dark room, experiencing eyestrain, or motion sickness during the trial. Otherwise, there are no foreseeable risks in this research project. You can be assured that the researcher will be present with you throughout the entire study duration and that you can take a rest break at any point of the trial. Apart from giving up your time, we do not expect that there will be any risk or inconvenience associated with taking part in this study.

Who will have access to my information?
The information collected in this research will be re-identifiable (coded). This means that we will remove identifying information on any data or sample and replace it with a code. Only the research team will have access to the information we collect in this research and the code to match your name. Any information we collect will be treated as confidential and used only in this project.

Electronic data will be password-protected and hard copy data will be in locked storage. The information we collect in this study will be kept under secure conditions at Curtin University for 7 years after the research has ended and then it will be destroyed/kept indefinitely. You have the right to access, and request correction of, your information in accordance with relevant privacy laws. The results of this research may be presented at conferences or published in professional journals. You will not be identified in any results that are published or presented.

Will you tell me the results of the research?

A summary of the results will be available from the researcher on request once the study is completed. Results will not be individual but based on all the information we collected and reviewed as part of the research.

Do I have to take part in the research project?

Participation in this study is totally voluntary and you are under no obligation to take part in this study. If you decide to take part and then change your mind, you have the right to withdraw from the study at any time and without giving a reason. Please let us know you want to stop so we can make sure you are aware of any thing that needs to be done so you can withdraw safely. If you chose not to take part or start and then stop the study, it will not affect your relationship with the University, staff, or colleagues. If you chose to leave the study, we will destroy any information we have collected from you.

What happens next and who can I contact about the research?

If you have any questions or require any further information, please contact the following researchers.

Name of Principal Investigator: Dr Hoe Lee
Email: *H.lee@curtin.edu.au*

Name of Student Investigator: Miss Yi Huey Lim
E-mail: *Yihuey.lim@postgrad.curtin.edu.au*

If you decide to take part in this research we will ask you to sign the consent form. By signing, it is telling us that you understand what you have read and what has been discussed. Signing the consent indicates that you agree to be in the research project and have your health information used as described. Please take your time and ask any questions you have before you decide what to do. You will be given a copy of this information and the consent form to keep.

The following statement must be included in every information sheet:

Curtin University Human Research Ethics Committee (HREC) has approved this study (HREC number 28/2016). Should you wish to discuss the study with someone not directly involved, in particular, any matters concerning the conduct of the study or your rights as a participant, or you wish to make a confidential complaint, you may contact the Ethics Officer on (08) 9266 9223 or the Manager, Research Integrity on (08) 9266 7093 or email hrec@curtin.edu.au.

PARTICIPANT INFORMATION STATEMENT

HREC Project Number:	HR 28/2016
Project Title:	*The contribution of central and peripheral vision on postural control during standing in adults with Autism Spectrum Disorders*
Principal Investigator:	*Dr Hoe Lee, Associate Professor*
Student researcher:	*Yi Huey Lim*
Version Number:	*4*
Version Date:	*15/06/2017*

What is the Project About?
Having good balance is important for movement. Our ability to balance depends on the information from our ears, eyes, and touch. Eyesight has an important role in balance because we need to see in order to interact with our environment. However, there is insufficient knowledge in understanding how vision affects the way people stand or move.

This study aims to investigate the impact of vision on balance in adults. The study will require participants without Autism Spectrum Disorder (ASD).

Who is doing the Research?
The project is being conducted by Yi Huey Lim and this research will contribute to a higher educational qualification of this student researcher. The results of this research project will be used by Yi Huey Lim to obtain a Doctorate of Philosophy at Curtin University.

Why am I being asked to take part and what will I have to do?
You have been asked to take part in this study because you have identified yourself as:

- Between 18 – 50 years old
- Able to provide written consent in English
- Can see afar without wearing spectacles
- Willing to stand for 30 minutes (with interval rest breaks)
- Have no history of seizure

If you agree to participate in this study, you will be required to complete the social responsiveness scale test, visual acuity, IQ, sensory profile, and motor skill assessments. You will be required to stand still on a force platform in bare feet, in the dark and watch a screen with moving dots. In addition, you will be required to wear a cap that will measure your brain activity during the study. The study will take approximately 3 hours to complete. The study will be conducted in Curtin University. There will be no cost to you for taking part in this research and you will be reimbursed for your inconvenience with a $20 Coles/Myer gift card upon completion of the study.

We would like you to consider allowing us to send you information about future research projects. Once you receive the information it is your choice if you decide to take part or not.

Are there any benefits to being in the research project?
There may be no direct benefit to you for participating in this research. However, your participation in this study may benefit people with ASD in the future. We hope the results of this research will allow us to:

- develop education programs
- add to the knowledge we have about this condition

Are there any risks, side-effects, discomforts or inconveniences from being in the research project?
The possible discomfort in this study may include feeling uncomfortable being in a dark room, experiencing eyestrain, or motion sickness during the trial. Otherwise, there are no foreseeable risks in this research project. You can be assured that the researcher will be present with you throughout the entire study duration and that you can take a rest break at any point of the trial. Apart from giving up your time, we do not expect that there will be any risk or inconvenience associated with taking part in this study.

Who will have access to my information?
The information collected in this research will be re-identifiable (coded). This means that we will remove identifying information on any data or sample and replace it with a code. Only the research team will have access to the information we collect in this research and the code to match your name. Any information we collect will be treated as confidential and used only in this project.

Electronic data will be password-protected and hard copy data will be in locked storage. The information we collect in this study will be kept under secure conditions at Curtin University for 7 years after the research has ended and then it will be destroyed/kept indefinitely. You have the right to access, and request correction of, your information in accordance with relevant privacy laws. The results of this research may be presented at conferences or published in professional journals. You will not be identified in any results that are published or presented.

Will you tell me the results of the research?
A summary of the results will be available from the researcher on request once the study is completed. Results will not be individual but based on all the information we collected and reviewed as part of the research.

Do I have to take part in the research project?
Participation in this study is voluntary and you are under no obligation to take part in this study. If you decide to take part and then change your mind, you have the right to withdraw from the study at any time and without giving a reason. Please let us know you want to stop so we can make sure you are aware of any thing that needs to be done so you can withdraw safely. If you chose not to take part or start and then stop the study, it will not affect your relationship with the University, staff, or colleagues. If you chose to leave the study, we will destroy any information we have collected from you.

What happens next and whom can I contact about the research?
If you have any questions or require any further information, please contact the following researchers.

Name of Principal Investigator: Dr Hoe Lee
Email: *H.lee@curtin.edu.au*

Name of Student Investigator: Miss Yi Huey Lim
E-mail: *Yihuey.lim@postgrad.curtin.edu.au*

If you decide to take part in this research, we will ask you to sign the consent form. By signing, it is telling us that you understand what you have read and what has been discussed. Signing the consent indicates that you agree to be in the research project and have your health information used as described. Please take your time and ask any questions you have before you decide what to do. You will be given a copy of this information and the consent form to keep.

The following statement must be included in every information sheet:
Curtin University Human Research Ethics Committee (HREC) has approved this study (HREC number 28/2016). Should you wish to discuss the study with someone not directly involved, in particular, any matters concerning the conduct of the study or your rights as a participant, or you wish to make a confidential complaint, you may contact the Ethics Officer on (08) 9266 9223 or the Manager, Research Integrity on (08) 9266 7093 or email hrec@curtin.edu.au.

CONSENT FORM

HREC Project Number:	HR 28/2016
Project Title:	*The contribution of central and peripheral vision on postural control during standing in adults with Autism Spectrum Disorders*
Principal Investigator:	*Dr Hoe Lee, Associate Professor*
Student researcher:	*Yi Huey Lim*
Version Number:	*2*
Version Date:	*10/02/2016*

- I have read the information statement version listed above and I understand its contents.
- I believe I understand the purpose, extent and possible risks of my involvement in this project.
- I voluntarily consent to take part in this research project.
- I have had an opportunity to ask questions and I am satisfied with the answers I have received.
- I understand that this project has been approved by Curtin University Human Research Ethics Committee and will be carried out in line with the National Statement on Ethical Conduct in Human Research (2007) – updated March 2014.
- I understand I will receive a copy of this Information Statement and Consent Form.

Participant Name	
Participant Signature	
Date	

Declaration by researcher: I have supplied an Information Letter and Consent Form to the participant who has signed above, and believe that they understand the purpose, extent and possible risks of their involvement in this project.

Researcher Name	
Researcher Signature	
Date	

☐ Please tick the box if you allow us to send you information about future research projects. Once you receive the information, it is your choice if you decide to take part or not.

Preferred method of contact: Telephone / Email ____

PARENT INFORMATION FORM FOR CHILD'S RESEARCH PARTICIPATION

HREC Project Number:	HR 28/2016
Project Title:	*The contribution of central and peripheral vision on postural control during standing in individuals with autism spectrum disorder*
Principal Investigator:	*Associate Professor Hoe Lee*
Student researcher:	*Yi Huey Lim*
Version Number:	*2*
Version Date:	*15/06/2017*

Your child is being asked to take part in a research study. This form has important information about the reason for doing this study, what we will ask your child to do, and the way we would like to use information about your child if you choose to allow your child to be in the study.

What is the Project About?

Having good balance is important for movement. Our ability to balance depends on the information from our ears, eyes, and touch. Eyesight has an important role in balance because we need to see in order to interact with our environment. However, there is insufficient knowledge in understanding how visual information affects the way people stand or move.

This study aims to investigate the influence of visual information on balance in children with autism spectrum disorder (ASD). The study will require children with ASD.

Who is doing the Research?

The project is being conducted by Yi Huey Lim and this research will contribute to a higher educational qualification of this student researcher. The results of this research project will be used by Yi Huey Lim to obtain a Doctorate of Philosophy at Curtin University.

Why is my child being asked to take part and what will my child be asked to do?
Your child has been asked to take part in this study because your child has been identified as:

- Between 8 – 12 years old
- Has either been clinically diagnosed with ASD or Asperger Syndrome
- Or is typically developed
- Can see afar without wearing spectacles
- Willing to stand for 30 minutes (with interval rest breaks)
- Has no history of epilepsy or seizure

If your child agrees to participate in this study, your child will be required to complete the social responsiveness scale test, visual acuity, IQ, sensory profile, repetitive behaviour, and motor skill assessments. In addition, your child will be asked to stand still on a force platform, in a dimly lit room, and watch a video with moving dots. The study will take approximately 3 hours to complete. The study will be conducted in Curtin University. There will be no cost to your child for taking part in this research and your child will receive a token of appreciation for completing the study.

Are there any benefits to being in the research project?
There may be no direct benefit to you for participating in this research. However, your participation in this study may benefit individuals with ASD in the future. We hope the results of this research will allow us to:

- develop intervention programs
- add to the knowledge we have about this condition

Are there any risks, side effects, discomforts, or inconveniences from being in the research project?
The possible discomfort in this study may include feeling uncomfortable being in a dimly lit room, experiencing eyestrain, or motion sickness during the trial. Otherwise, there are no foreseeable risks in this research project. You can be assured that the researcher will be present with your child throughout the entire study duration and that your child can take a rest break at any point of the trial. Apart from giving up your child's time, we do not expect that there will be any risk or inconvenience associated with taking part in this study.

Who will have access to my child's information?
The information collected in this research will be re-identifiable (coded). This means that we will remove identifying information on any data or sample and replace it with a code. Only the research team will have access to the information we collect in this research and the code to match your child's name. Any information we collect will be treated as confidential and used only in this project.

Electronic data will be password-protected and hard copy data will be in locked storage. The information we collect in this study will be kept under secure conditions at Curtin University for a minimum of 7 years after publication or project completion, or the subject/s have reached 25 years of age, whichever is later, then it will be destroyed/kept indefinitely. You have the right to access, and request correction of, your child's information in accordance with relevant privacy laws. The results of this research may be presented at conferences or published in professional journals. Your child will not be identified in any results that are published or presented.

Will you tell me the results of the research?
A summary of the results will be available from the researcher on request once the study is completed. Results will not be individual but based on all the information we collected and reviewed as part of the research.

Does my child has to take part in the research project?
Participation in this study is voluntary and your child is under no obligation to take part in this study. Your child may withdraw from the study at any time and without giving a reason. Please let us know you want to stop so we can make sure you are aware of any thing that needs to be done so you can withdraw safely. If your child chooses to leave the study, the researchers will ask if the information already collected from your child can be used.

What happens next and whom can I contact about the research?
If you have any questions or require any further information, please contact the following researchers.

Name of Principal Investigator: Dr Hoe Lee
Email: *H.lee@curtin.edu.au*

Name of Student Investigator: Miss Yi Huey Lim
E-mail: *Yihuey.lim@postgrad.curtin.edu.au*

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PARENT INFORMATION FORM FOR CHILD'S RESEARCH PARTICIPATION

HREC Project Number:	HR 28/2016
Project Title:	*The contribution of central and peripheral vision on postural control during standing in individuals with autism spectrum disorder*
Principal Investigator:	*Associate Professor Hoe Lee*
Student researcher:	*Yi Huey Lim*
Version Number:	*2*
Version Date:	*15/06/2017*

Your child is being asked to take part in a research study. This form has important information about the reason for doing this study, what we will ask your child to do, and the way we would like to use information about your child if you choose to allow your child to be in the study.

What is the Project About?

Having good balance is important for movement. Our ability to balance depends on the information from our ears, eyes, and touch. Eyesight has an important role in balance because we need to see in order to interact with our environment. However, there is insufficient knowledge in understanding how vision influences the way people stand or move.

This study aims to investigate the impact of vision on balance in children with autism spectrum disorder (ASD). The study will require typically developing children.

Who is doing the Research?

The project is being conducted by Yi Huey Lim and this research will contribute to a higher educational qualification of this student researcher. The results of this research project will be used by Yi Huey Lim to obtain a Doctorate of Philosophy at Curtin University.

Why is my child being asked to take part and what will my child be asked to do?
Your child has been asked to take part in this study because your child has been identified as:

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- Can see afar without wearing spectacles
- Willing to stand for 30 minutes (with interval rest breaks)
- Has no history of epilepsy or seizure

If your child agrees to participate in this study, your child will be required to complete the social responsiveness scale test, visual acuity, IQ, sensory profile, repetitive behaviour, and motor skill assessments. In addition, your child will be asked to stand still on a force platform in bare feet, in a dimly lit room and watch a video with moving dots. The study will take approximately 3 hours to complete. The study will be conducted in Curtin University. There will be no cost to your child for taking part in this research and your child will receive a token of appreciation for completing the study.

Are there any benefits to being in the research project?
There may be no direct benefit to you for participating in this research. However, your participation in this study may benefit individuals with ASD in the future. We hope the results of this research will allow us to:

- develop intervention programs
- add to the knowledge we have about this condition

Are there any risks, side effects, discomforts, or inconveniences from being in the research project?
The possible discomfort in this study may include feeling uncomfortable being in a dimly lit room, experiencing eyestrain, or motion sickness during the trial. Otherwise, there are no foreseeable risks in this research project. You can be assured that the researcher will be present with your child throughout the entire study duration and that your child can take a rest break at any point of the trial. Apart from giving up your child's time, we do not expect that there will be any risk or inconvenience associated with taking part in this study.

Who will have access to my child's information?
The information collected in this research will be re-identifiable (coded). This means that we will remove identifying information on any data or sample and replace it with a code. Only the research team will have access to the information we collect in this research and the code to match your child's name. Any information we collect will be treated as confidential and used only in this project.

Electronic data will be password-protected and hard copy data will be in locked storage. The information we collect in this study will be kept under secure conditions at Curtin University for a minimum of 7 years after publication or project completion, or the subject/s have reached 25 years of age, whichever is later, then it will be destroyed/kept indefinitely. You have the right to access, and request correction of, your child's information in accordance with relevant privacy laws. The results of this research may be presented at conferences or published in professional journals. Your child will not be identified in any results that are published or presented.

Will you tell me the results of the research?
A summary of the results will be available from the researcher on request once the study is completed. Results will not be individual but based on all the information we collected and reviewed as part of the research.

Does my child has to take part in the research project?
Participation in this study is voluntary and your child is under no obligation to take part in this study. Your child may withdraw from the study at any time and without giving a reason. Please let us know you want to stop so we can make sure you are aware of any thing that needs to be done so you can withdraw safely. If your child chooses to leave the study, the researchers will ask if the information already collected from your child can be used.

What happens next and who can I contact about the research?
If you have any questions or require any further information, please contact the following researchers.

Name of Principal Investigator: Dr Hoe Lee
Email: *H.lee@curtin.edu.au*

Name of Student Investigator: Miss Yi Huey Lim
E-mail: *Yihuey.lim@postgrad.curtin.edu.au*

If you decide to allow your child to take part in this research, we will ask you to sign the consent form. By signing, it is telling us that you understand what you have read and what has been discussed. Please take your time and ask any questions you have before you decide what to do. You will be given a copy of this information and the consent form to keep.

The following statement must be included in every information sheet:
Curtin University Human Research Ethics Committee (HREC) has approved this study (HREC number 28/2016). Should you wish to discuss the study with someone not directly involved, in particular, any matters concerning the conduct of the study or your rights as a participant, or you wish to make a confidential complaint, you may contact the Ethics Officer on (08) 9266 9223 or the Manager, Research Integrity on (08) 9266 7093 or email hrec@curtin.edu.au.

CONSENT FORM

HREC Project Number:	HR 28/2016
Project Title:	*The contribution of central and peripheral vision on postural control during standing in individuals with autism spectrum disorders*
Principal Investigator:	*Associate Professor Hoe Lee*
Student researcher:	*Yi Huey Lim*
Version Number:	2
Version Date:	*15/06/2017*

- I have read the information statement version listed above and I understand its contents.
- I believe I understand the purpose, extent, and possible risks of my involvement in this project.
- I voluntarily consent to my child to take part in this research project.
- I have had an opportunity to ask questions and I am satisfied with the answers I have received.
- I understand that this project has been approved by Curtin University Human Research Ethics Committee and will be carried out in line with the National Statement on Ethical Conduct in Human Research (2007) – updated March 2014.
- I understand I will receive a copy of this Information Statement and Consent Form.

I agree to take part in the project "*The contribution of central and peripheral vision on postural control during standing in individuals with autism spectrum disorders*".

Name of Child	
Signature	
Date	

Parent/Legal Guardian's Name	
Relationship to child	
Parent/Legal Guardian's Signature	
Date	

Declaration by researcher: I have supplied an Information Letter and Consent Form to the participant who has signed above, and believe that they understand the purpose, extent, and possible risks of their involvement in this project.

Researcher Name	
Researcher's Signature	
Date	

Appendix E Participant particular form

Curtin University

Visual Field

Demographic Questionnaire

Date:

Time:

Name:

Number:

Age:	___________
Gender:	Female / Male
Hand Dominance	Right / Left
Have you been clinically diagnosed with Autism Spectrum Disorder? By whom?	Yes / No Doctor / Psychologist / ___________
Past Medical History	___________
Past Medication History	___________

To be completed by assessors

EDTRS score	___________
WASI score	___________
MAND score	___________
SRS score	___________

Visual field, Demographic questionnaire Version 1, 17/12/2015 Page 1 of 1

Appendix F Adverse event management plan

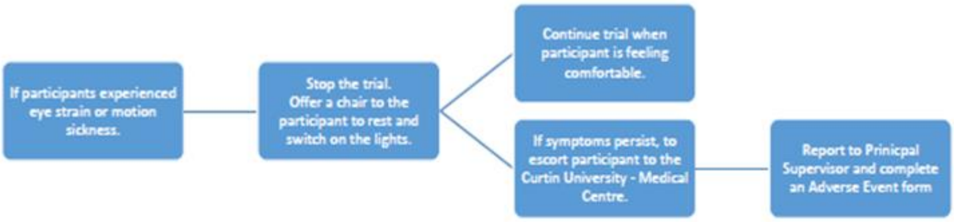
Curtin University

Adverse Event Management Plan

Before start of study:

Researcher will ensure participants are aware that if they have a history of psychiatric condition, epilepsy, seizure or neurological disorders they cannot participate in the study. Participants will also be asked regarding any history of motion sickness and will be closely monitored during the study.

During the study:



Information of Curtin University – Medical Centre

Location: Bentley Campus, Building 109, Level 1

Contact number: +61 8 9266 7345

Opening house: Monday to Friday, 8:30am to 4:30pm

Nurse Availability: Monday to Friday, 8:00am to 6:00pm

Information of Prinicipal Supervisor

Name: Dr Hoe Lee

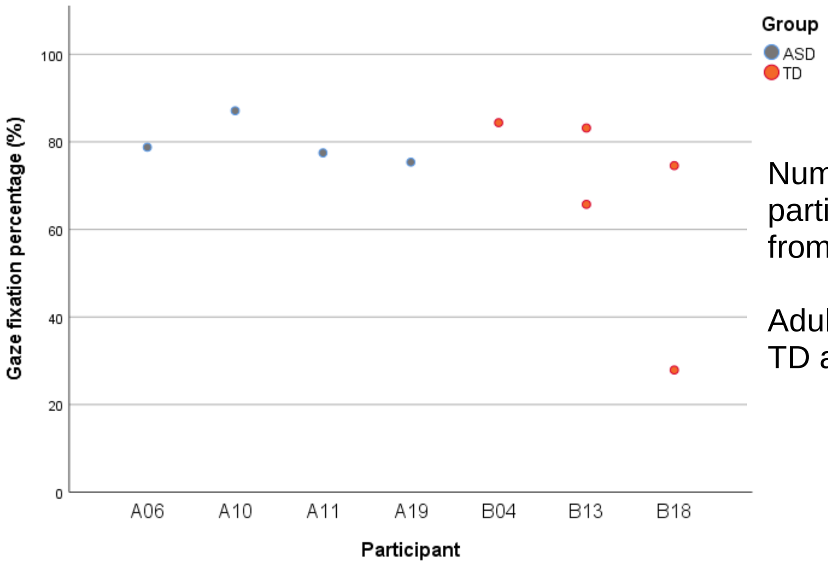
Contact Details: +61 8 9266 4652

Adverse Event Management Plan, Version 1, 10/02/2016 Page 1 of 1

Appendix G Post hoc analysis of eye-tracking data

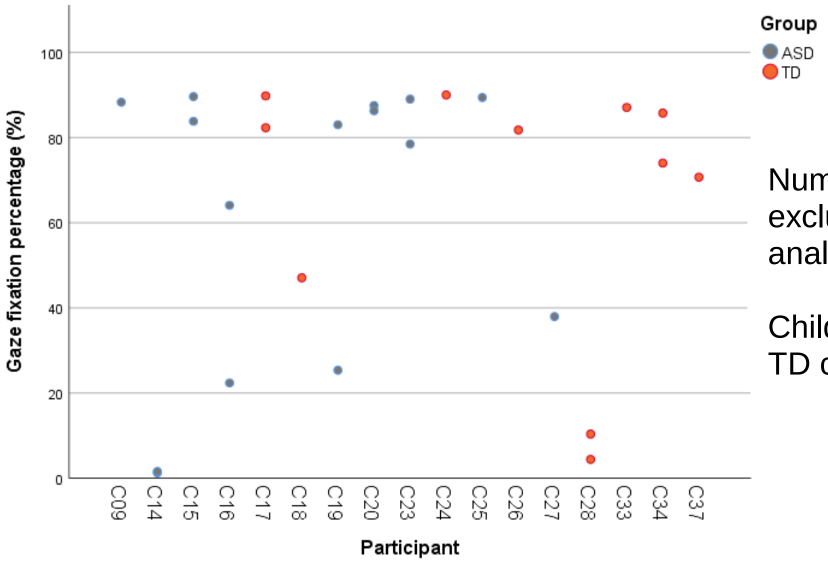
The following data presents the number of participants whose data were excluded from statistical analysis due to not meeting the experimental protocol of requiring each individual data to achieve at least 90% gaze fixation percentage (Refer to Chapter 2.2.6, “Data processing and statistical analysis”). The data from seven different visual conditions, consisting of children and adults with autism spectrum disorder (ASD) and typically developing/developed (TD) controls, are presented below.

Static condition



Number of participants excluded from data analysis

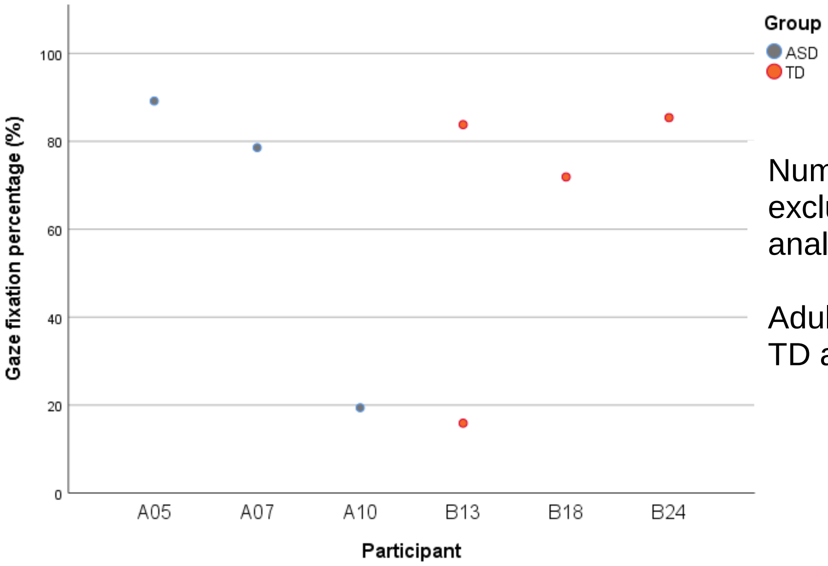
Adults with ASD = 4
TD adults = 3



Number of participants excluded from data analysis

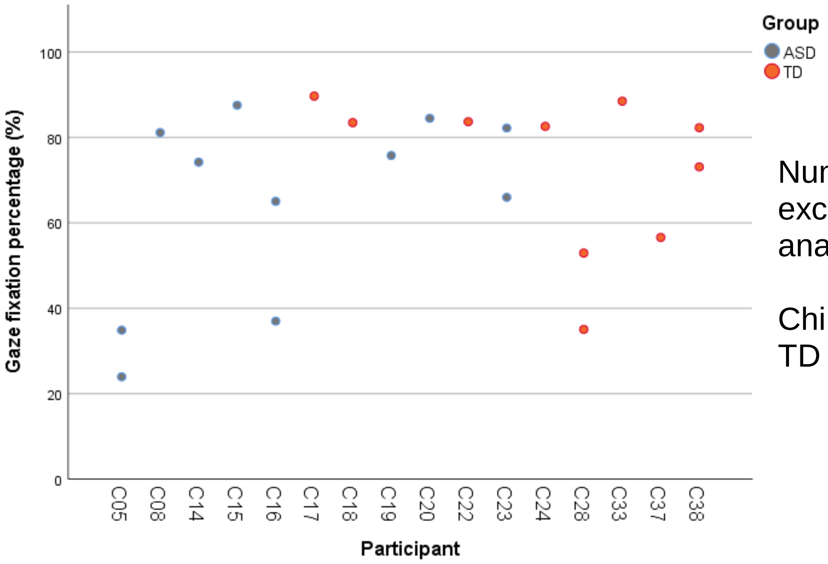
Children with ASD = 9
TD children = 8

Optic flow in contraction, full visual field condition



Number of participants excluded from data analysis

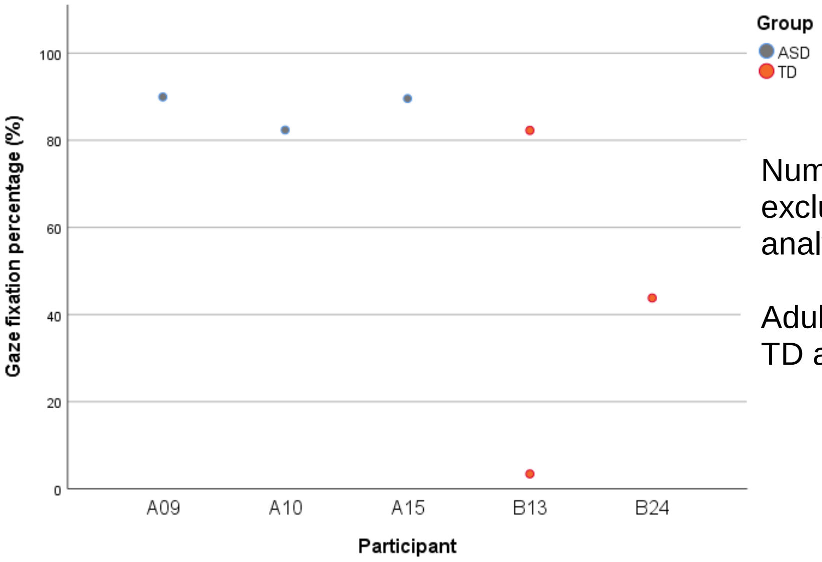
Adults with ASD = 3
TD adults = 3



Number of participants excluded from data analysis

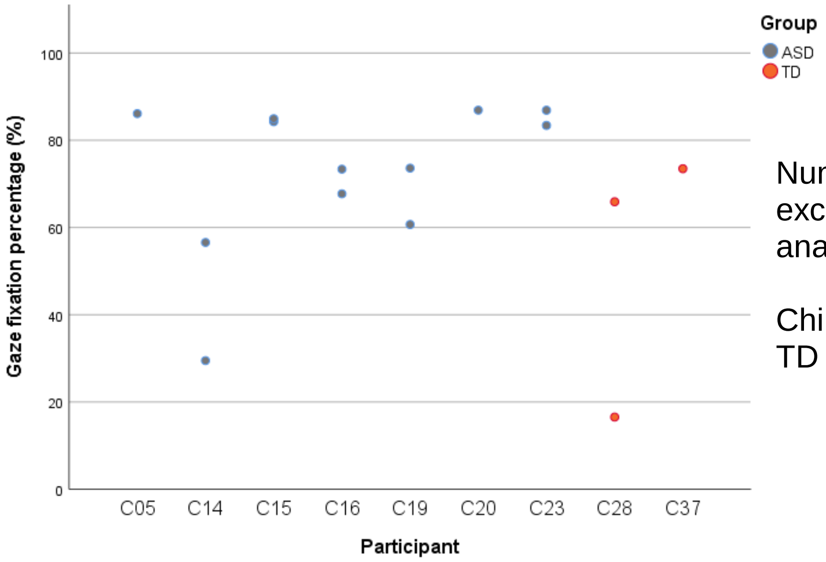
Children with ASD = 8
TD children = 8

Optic flow in contraction, central visual field condition



Number of participants excluded from data analysis

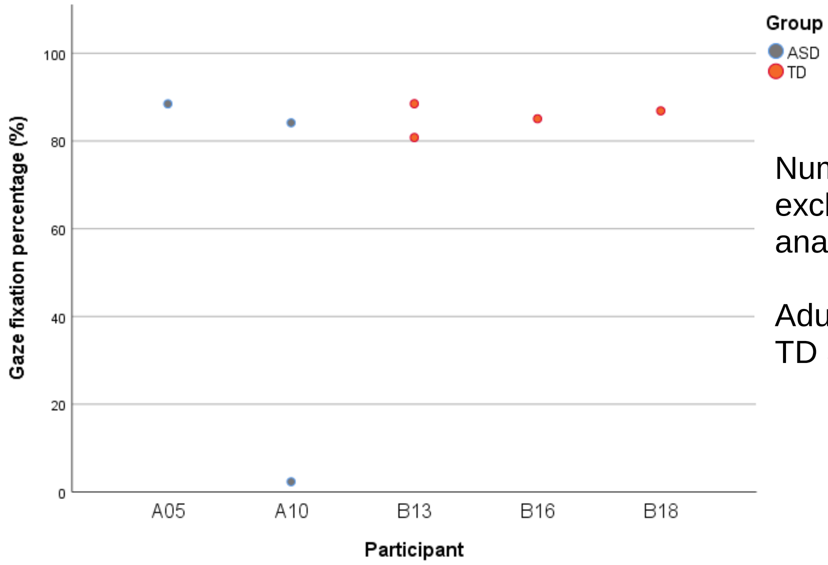
Adults with ASD = 3
TD adults = 2



Number of participants excluded from data analysis

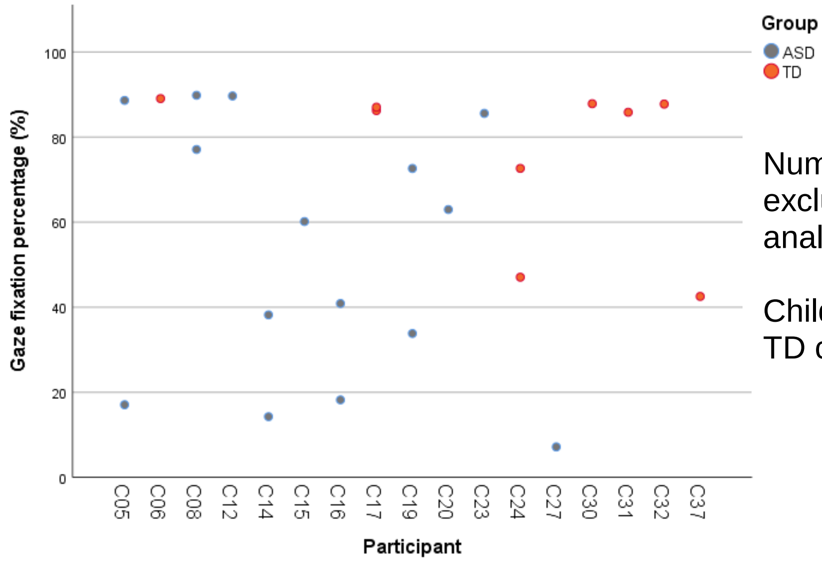
Children with ASD = 7
TD children = 2

Optic flow in contraction, peripheral visual field condition



Number of participants excluded from data analysis

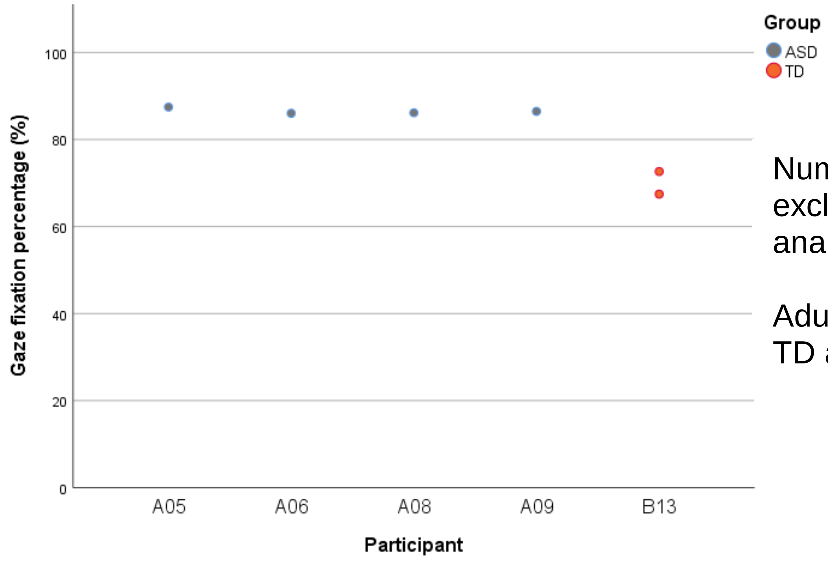
Adults with ASD = 2
TD adults = 3



Number of participants excluded from data analysis

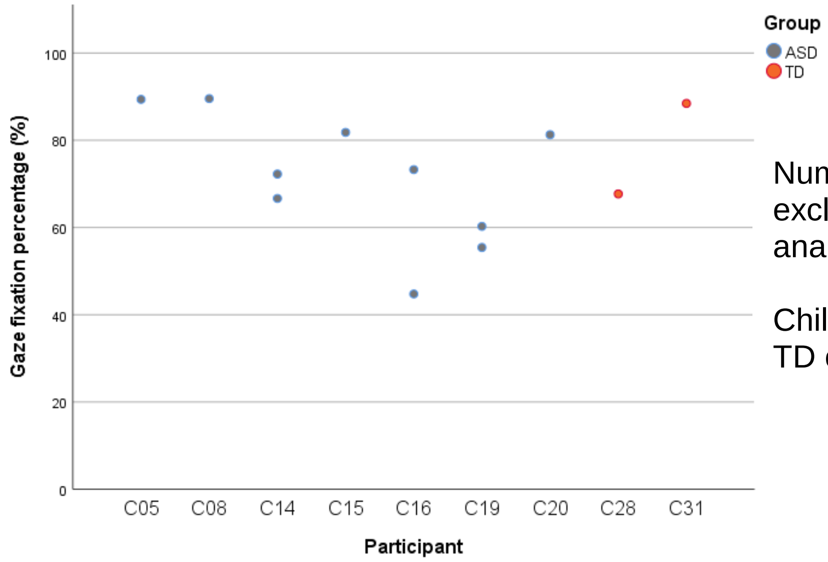
Children with ASD = 10
TD children = 7

Optic flow in expansion, full visual field condition



Number of participants excluded from data analysis

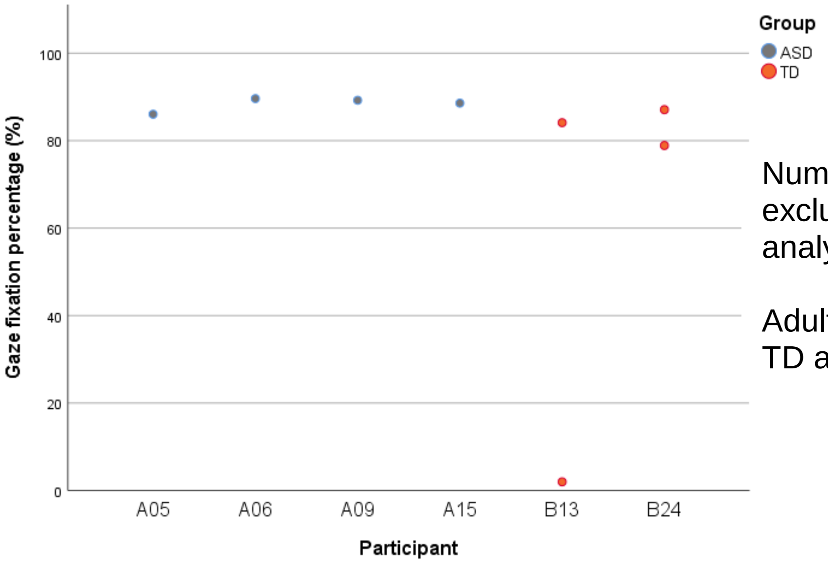
Adults with ASD = 4
TD adults = 1



Number of participants excluded from data analysis

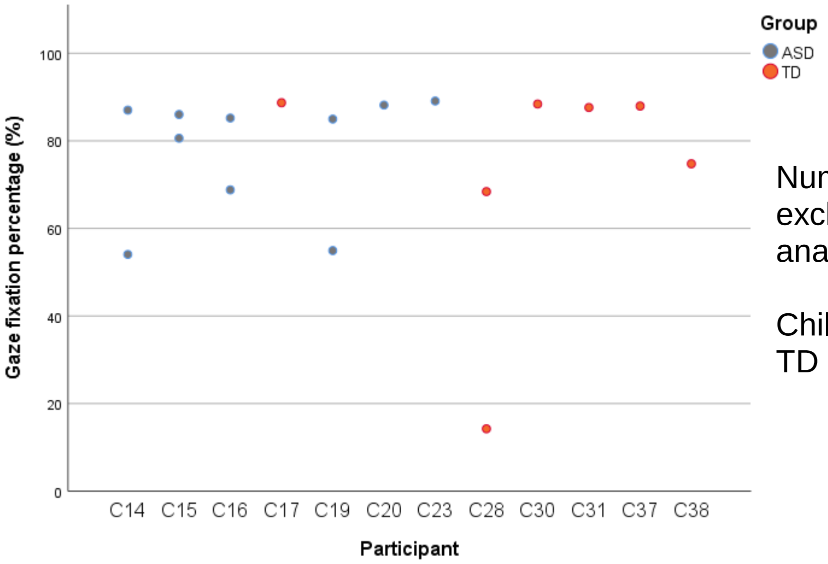
Children with ASD = 7
TD children = 1

Optic flow in expansion, central visual field condition



Number of participants excluded from data analysis

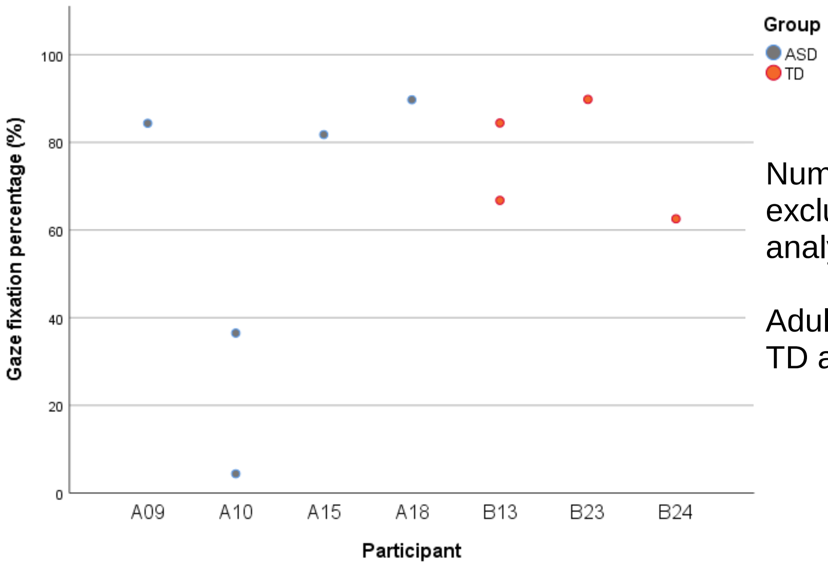
Adults with ASD = 4
TD adults = 2



Number of participants excluded from data analysis

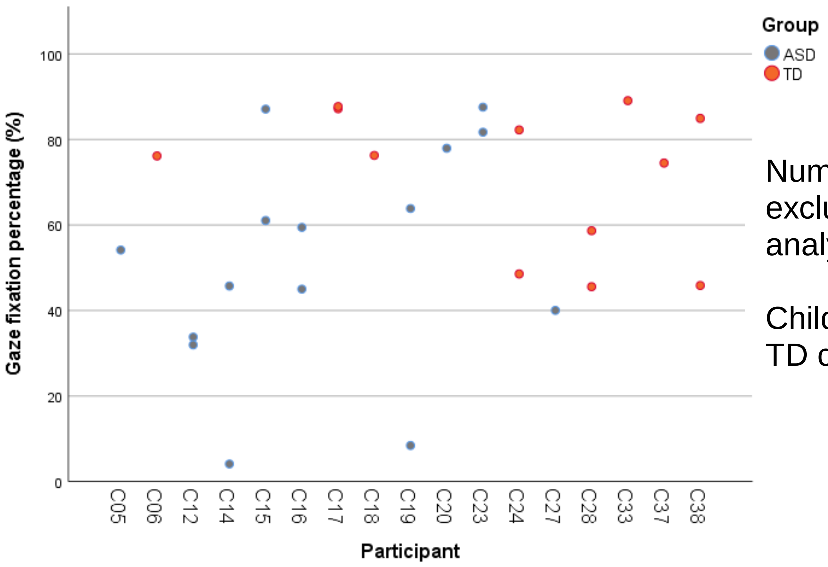
Children with ASD = 6
TD children = 6

Optic flow in expansion, peripheral visual field condition



Number of participants excluded from data analysis

Adults with ASD = 4
TD adults = 3



Number of participants excluded from data analysis

Children with ASD = 9
TD children = 8